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DIFFUSION IN ORE GENESIS.

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IN making a close study of the genesis of the remarkable silver ores at Cobalt, Ontario, from 1915 to 1918 the writer conceived that the major joints along which the mineral deposits were formed must have been sealed in the first stages of deposition, and that no process could have functioned to bring about the further marginal accretions by which the veins grew to their present widths, save only that of diffusion. This idea was expressed in two papers published in 1920[1] and 1922[2] respectively, and was tested in an experiment performed at the University of California at Berkeley, and reported in the paper of 1922.

The Berkeley experiment was purely qualitative, and although successful in demonstrating diffusion of potassium sulphide through marble, was not adequate to quiet the misgivings of fellow geologists who doubted the potency of diffusion in large scale operation as contrasted with the fancied greater potency of water circulation as a carrier of mineral. Therefore in 1926–7 at the University of California at Los Angeles the writer performed a more elaborate and careful quantitative experiment to establish the rate of diffusion in rock. The results have just been secured and with such success as to require announcement and discussion.

[1] "Diffusion in Vein Genesis at Cobalt," ECON. GEOL., vol. 15, No. 2.

[2] "Genesis of the Ores of the Cobalt District, Ontario, Canada," Univ. of Cal. Pub., Geol. Ser., vol. 13, No. 7.

THE QUANTITATIVE EXPERIMENT.

If it is admitted that a chemical substance may diffuse through rock the important question arises as to the mode of migration. There is much good evidence, superfluous here, indicating that water does not occupy the molecular interspaces of crystalline media, at least in the anhydrous minerals; but in the kaolinization, serpentinization and other alteration of minerals there is abundant evidence familiar to every microscopist that water may fill the pore-spaces of minerals and rocks, that is in cleavages, fractures, and mineral contacts and interstices. Such water may be assumed without demonstration to be present in all rocks although incapable of showing itself by mineral hydration and other alteration until the rock containing it enters conditions in which the minerals become unstable; and the mode of dispersion of this water must be supposed to be in films.

In the present experiment this was assumed to be true; and marble was selected as the medium for experimentation because of the strength and multiplicity of the calcite cleavages. The initial plan was to obtain the rate of diffusion of a given salt first in marble, then in granite, and then in such other rocks as diabase, anorthosite, trachyte, and sandstone, subsequently using some very different salt for each of them; but on second thought this plan was abandoned because of the impossibility of trying all combinations under all possible geologic conditions, it being thought sufficient to demonstrate the principle and determine the rate for one single set of conditions.

A block of white Vermont marble was cut to a size 38 x 46 cms. on the top and 32 cms. in depth. It was smoothed on ends, sides and bottom, and polished on top. Careful inspection failed to reveal any fracture or flaw in the block. Faint irregular streaks of dark discoloration, perhaps representing nearly effaced bedding, extending from end to end; but careful study on the polished and other faces proved the crystalline homogeneity of the block to be virtually perfect.

Vertical holes 12 mm. in diameter and 16 cm. deep were drilled in the polished top of the block, following the pattern indicated in

Fig 1, in such a manner and with such care as to insure that no fractures would be produced in the sides of the holes.

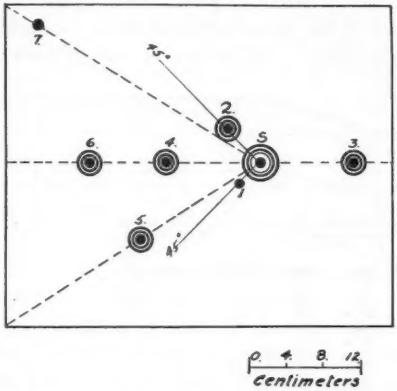

FIG. 1. Plan of top of marble block and arrangement of holes. Black rings consist of mixed beeswax and resin; outer white rings consist of silver nitrate solution.

In order to eliminate capillarity as a means of assisting migration of the salt which was to be introduced, the block was saturated with water before the experiment was begun, and was kept in that condition throughout the experiment. To this end the block was placed in a waterproofed iron tank 45 x 50 cm. in plan and 32 cm. in depth, the block resting upon wooden strips in the tank so as to extend 4 cm. above its rim (Fig. 2). The tank was perforated for overflow just below the rim, and equipped with a drain, water being kept in it to the overflow level. Eight and one half months were allowed for the saturation of the marble by means of capillarity, tank and holes being kept full throughout that period, and saturation not being assumed until the level of the distilled water in the holes ceased to change. During that time the temperature was stabilized and absolute humidity maintained over the top of the block.

The humidity was secured by covering the block with a glass

cover of such size as to clear the marble by a good margin and not to touch the tank, being suspended from narrow wood strips on the tank rim by means of aluminum hangers which permitted the glass sides of the cover to extend down well below the water surface in the tank. Uniformity of temperature was secured

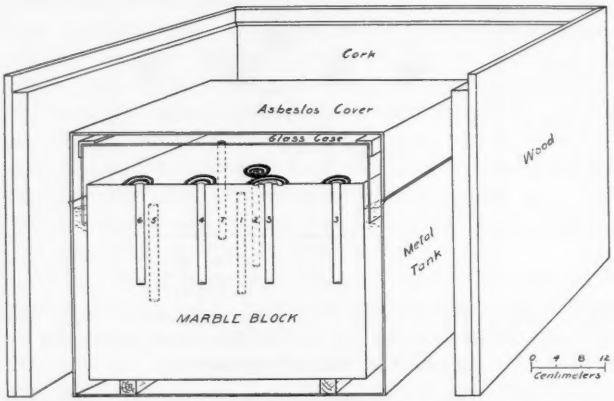

FIG. 2. Arrangement of marble block in containers, to maintain saturation, humidity, and constant temperature.

by housing tank and all in a thick well-made wooden box lined with cork to a thickness of an inch, a smaller heavy asbestos-board cover being fitted over the glass cover in such a manner as to make an air-tight contact with the tank rim. Then within the ample wood-cork housing, a 100-watt lamp was mounted on a porcelain stand and connected with a suspended thermostat accompanied by a thermometer. By this means a temperature of 70 degrees Fahrenheit was maintained throughout the entire experiment.

The tank was filled with water, and the saturation started on January 20, 1926. On October 5 of the same year potassium iodide was introduced into the central (*S*) hole in the form of C. P. crystals in sufficient quantity to saturate the distilled water

with which the remaining space in the hole was filled. At the same time the other holes were filled to their collars with distilled water, and the experiment started.

None of the holes were plugged in any manner; but all were left open and accessible. This eliminated the difficulty of finding a seal which would attach to the sides of the holes leaving less pore-space than existed within the marble. It also gave a free vision and access to the holes for the purpose of replenishing the KI in the *S* hole and the water in the other holes. The constant humidity prevented capillary creep of the solution, through any possible crust of evaporated salt, from *S* to the other holes over the surface of the marble; and the constancy of temperature tended to prevent the precipitation of dew on the rock surface. through which KI might diffuse from hole to hole. In order to eliminate any remaining possibility that diffusion might take place over the rock surface through a film of moisture adsorbed to the marble, two rings or moats of silver nitrate solution were placed around the *S* hole with the idea that KI would there be held as AgI. On November 23d, after the spread of the field of diffusion within the marble had been twice measured, dew-like spots of water were detected about *S*. It was noted that they were largest and most numerous just outside the outer moat of $AgNO_3$, dwindling rapidly to nothing within a radius of two inches. A careful qualitative test showed them to contain KI; and it was concluded that the salt had migrated along radii from the depths of the hole to the rock surface in sufficient quantity to cause the hygroscopic accumulation of moisture in globules. This alarm was met by surrounding each of the other holes with a protective ring of $AgNO_3$. These rings or moats were held in place by dams of a cement consisting of a mixture of beeswax and resin. As subsequent results indicated, this eliminated the last chance of error resulting from the movement of KI across the rock surface.

On October 28th the first qualitative test for iodine showed its presence in holes Nos. 1, 2, and 3. Careful quantitative measurements were at once made to determine the amount of iodine

in each of these holes. It was found that the holes in the above order showed KI per cubic centimeter of solution to exist in the amounts respectively: 8.12 mgms., 1.78 mgms., and 0.08 mgms.

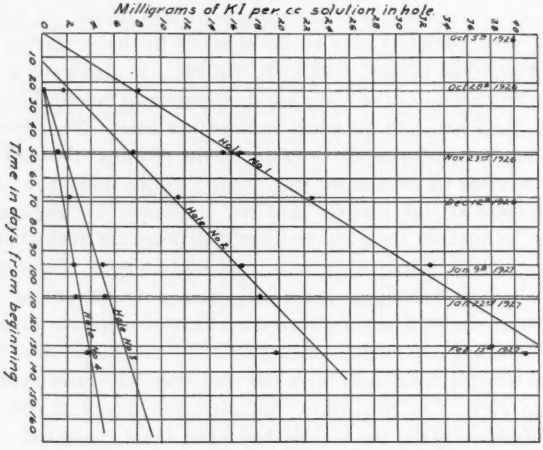

FIG. 3.

Thereafter qualitative and quantitative tests followed at frequent intervals as the field of diffusion spread steadily through the marble block. The results of these determinations are shown in Figs. 3, 4, 5.[3]

On the 26th of May, 1927, iodine having been detected in immeasurable amount in hole No. 6 ten days previous, the experiment was concluded. The determinations of January 22d, and February 15th, corroborated by an examination of *S* hole, indicated that the concentration of KI had been allowed to fall below

[3] Both kinds of tests were made by withdrawing, each time, two cubic centimeters of solution from a given hole, and replacing them with an equal volume of distilled water, the withdrawn solution being tested by shaking in a test tube with 4 cc. $Fe_3(NO_3)6.9H_2O$ and 2 cc. $C Cl_4$ acidulated with HNO_3, the iodine showing itself as a pink coloration, and being analyzed by titration with a standard solution of KIO_3 in the presence of 2cc. Conc. HCl to a clear solution.

saturation, thus vitiating the results slightly. However, enough data had already been obtained to serve the purpose of the investigation; and it was decided to begin the reversal experiment by

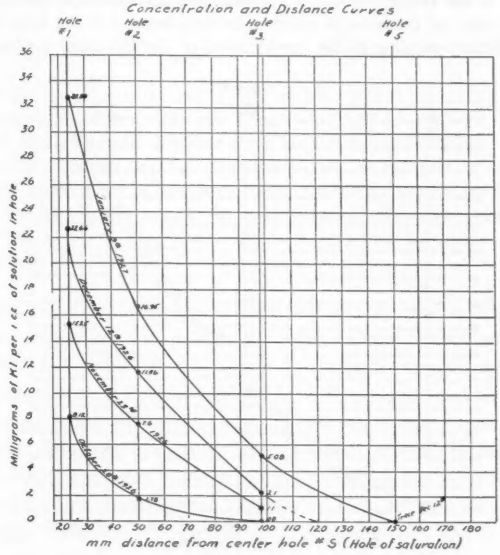
Concentration and Distance Curves
Hole #1
Hole #2
Hole #3
Hole #5
Milligrams of KI per 1 cc of solution in hole
mm distance from center hole #5 (Hole of saturation)

FIG. 4.

introducing $AgNO_3$ crystals into hole No. 6 to the full capacity of the hole. The aim in this proceeding was to abandon quantitative methods and to see what would happen in the way of forming a deposit of AgI in the hole or in the marble adjacent, precipitation reducing the KI diffusion gradient to zero at that point, thus causing all of the KI in the marble and tank ultimately to move and concentrate there in a miniature mineral deposit.

The mathematical aspects of the results have been indicated by Mr. J. H. Ransome [4] of the Department of Physics at the University, as follows:

[4] Mr. Ransome hopes soon to present a different and probably an analytical solution to the mathematical problem, notice of which will be given at the time.

Radial diffusion in a cylinder is governed by the law expressed by

$$\frac{\partial u}{\partial t} = K\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r}\right),$$

where u is the concentration of the diffusing quality; r is the distance from the axis, of the point at which u is considered; t is the time, and K is a coefficient peculiar to the combination of the diffusing quality with

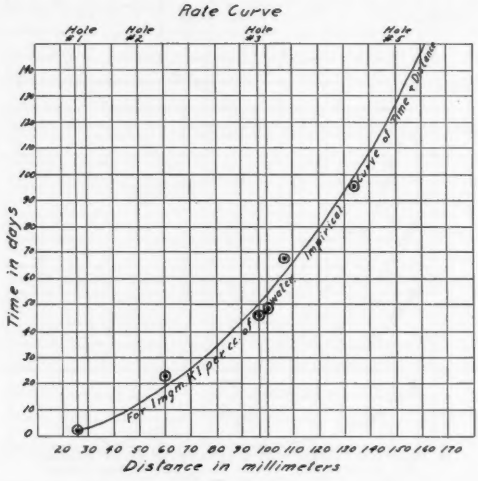

FIG. 5.

the medium through which it diffuses. By values of this quantity different diffusions are compared. It is numerically defined as the quantity of the diffusing quality which passes in unit time through unit area of a slab of unit thickness having unit difference of concentration between its faces.

If we may take the concentrations measured in the experiment in constant ratio to the corresponding concentrations in the marble adjacent to the holes, we may substitute for u in the above equation, its equivalent ev where v is the concentration (mgm/cc) in the test hole. Then since e is constant, it is removed from the derivatives and cancels out of the equation.

The value of the coefficient in the equation

$$\frac{\partial v}{\partial t} = K\left(\frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r}\right)$$

can be most easily determined from the experimental relations between v, r, and t by graphical means. This method is simplified in the present problem by the observation that the concentration-distance curves are very closely exponential in form. Thus from the relation $v = v_1 e^{-\mu(r-r_1)}$, we may determine by differentiation

$$\frac{\partial v}{\partial r} = -\mu v \qquad \text{and} \qquad \frac{\partial^2 v}{\partial r^2} = \mu^2 v.$$

From the concentration-time curves we may obtain the values of $\delta v/\delta t$, by graphically determining the slopes which at $r = 3.7$ cm. and $r = 6.0$ cm. are practically constant for a large interval of time.

Having obtained, in this way, the values of the partial derivatives, nothing remains but to substitute them in the diffusion equation and then solve for K. In this manner we have found by taking the mean of several results, $K = 1$ (cm.^{2}/day), which is very near the value of the coefficient of diffusion of potassium iodide in water.

The experiment just described has amply demonstrated that potassium iodide will diffuse through Vermont marble at a rate of the same order of magnitude as through massive water, and even, perhaps, a little faster. The salt ionizes readily, and the pore-spaces of the rock are numerous, large, and tabular. Nevertheless, any possibility of convection was eliminated by the absence of fractures. Perhaps, and probably, the diffusion measured was near the maximum for any rock medium; but diffusion through rock was demonstrated and measured; and it may be taken for granted that diffusion of other salts through the same rock or of the same salt through other rocks would proceed by the same principles and manner, though at different rates.

Probably it may safely be assumed that the diffusion took place through films of water disposed throughout the calcite cleavages and crystal contacts. Most likely a large factor in the rate of diffusion through the marble was the dispersion of a given volume of water through a large volume of rock, making it necessary for solute particles, seeking a given dilution in a given time, to move through a greater distance in that interval. Then the reason why it did not greatly exceed the rate of movement through massive water may have been the tortuousness of passageways.

GENERAL CONSIDERATIONS AND APPLICATIONS.

It may be that the several points made thus far will be so readily conceded by students of earth-physics and chemistry as to provoke no further thought, for the phenomena demonstrated have been investigated only within a small radius. However, it is now proposed that the diffusion measured in the experiment within a block of marble a few centimeters in size is the process immediately responsible for the formation of many metasomatic deposits of metalliferous minerals. In view of the tendency of economic geologists in the past each to regard his particular process as the "open sesame" by which the origin of ore deposits is to be explained, the writer wishes to avoid the same error, although he confesses that long consideration of the process and the close examination every year of many mineral deposits have resulted in a strong bias in that direction. He prefers, therefore, to propose: That diffusion is a large factor if not the major factor in the formation of metasomatic metalliferous deposits.

This takes the discussion back to the days of Sandberger,[5] his many examples of the close association of mineral deposits with metalliferous country-rock, and his defeated idea of the lateral movement of mineral-bearing waters. Thence it continues through a review of the divergent discussions that brought thought on the subject of ore-genesis to virtual stagnation in the tacit acceptance of the magical potency of hot ascending solutions with all their mysterious power of gathering mineral and moving with it through really inconceivable "fissures" and compact wall-rocks to the varied seats of deposition. It is to be regretted that time and space bar a voluminous refutation of these standard ideas and of the novel and swift emplacement of "ore-magmas" as championed by Mr. Spurr. Trusting that the mere presentation of the case of diffusion will suffice to inject it into the complex of genetic processes recognized by all honest students of ore-deposition, the writer must confine himself in the present paper to that single task.

Previous Objections to Diffusion.—The great barriers which

[5] "Untersuchungen über Erzgänge," 2d Ed., Weisbaden, 1885, p. 159.

have stood in the way of admitting the efficacy of diffusion in moving large amounts of mineral long distances are: (1) time, (2) radius of the field or spheroid of dilution, and (3) causes of solution and deposition. Probably the next, though lesser objection, is the frequent location of mineral deposits in loci of fracture and porosity where first thought would conceive water circulation to be possible not only during the period in which the open spaces are being sealed by deposition but even after all recognizable channels of convection and free water passage have been cemented.

Time.—The barrier of time exists only in the psychology of mankind, but in the reality of earth processes, human impatience is no factor.

The recent researches of Strutt,[6] Rutherford, Sir James Dewar, and others, have demonstrated beyond reasonable doubt that geologic time exceeds in its vast expanses even the poetic allowance made for it by the early fathers of geology. They have set the age of the recent and short Pleistocene period as more than a million years, and have assigned to many of the more ancient periods such greater ages as to make ridiculous all efforts to conceive metamorphism and mineral concentration as necessarily hasty processes. If a certain mineral deposit has been proven to belong to the Keewenawan or Cretaceous or Pleiocene period it may be allowed an epoch of millions of years in which to have formed.

Radius of Field.—The spheroid of dilution of a substance passing into solution in the depths of the earth must expand with exceeding slowness after reaching a certain radius. Becker[7] showed that sodium chloride diffusing through massive water in the course of 100,000 years would have progressed only 731 feet. But 100,000 years is only 1 per cent. of the time that may reasonably be allowed for the period of accumulation of some mineral deposits according to the quoted ideas of the magnitude of geologic time; and for argument's sake we may say that 2,000

[6] *Proceedings of the Royal Society*, 80A, p. 56.

[7] G. F. Becker, "Note on Computing Diffusion," *Am. Jour. Sci.*, ser. 4, vol. 3, p. 625.

feet shall be the maximum radius allowed for mineral migration through the pore spaces of rock in a spherical field of diffusion. Then, in the formation of ore deposits more than that distance from the supposed source of mineral, water circulation through unsealed passages may be invoked, where diffusion is equal in all directions; but that leaves a large proportion of significant metasomatic deposits within this assumed radius, and requires no passage of water through cemented fractures; it also permits the formation of mineral deposits nearly half a mile from any significant water course in a homogeneous medium. However, the radius of diffusion, or of the influence of precipitation, is not necessarily the theoretical radius of diffusion but a greatly modified form of it. The field of diffusion is rarely spherical but usually enormously distorted by lines of relatively easy diffusion; in consequence, the diffusing substance will move chiefly along some relatively open channel for the major part of its migration, the practical field of diffusion thus being, simply or complexly, essentially tabular. This would greatly alter the radius of diffusion because the volume or space to be occupied by the diffusing substance would thus be more or less elongated, and commonly would more than double the actual radius of diffusion.

Solution and Deposition.—Enquiry into the causes of solution and deposition is incumbent equally upon all students of ore-genesis except those who repose in the security of ore-magmas. The cause of deposition in metasomatic deposits must be that mysterious process of replacement by which a grain of rock yields place to a grain of mineral—volume-for-volume. It is not, strictly speaking, a chemical reaction, because it operates without regard to molecular weights. It would seem that the relations between the replaced and the replacing substances are so intimate that precipitation must be the effect rather than the cause of the phenomenon. In other words the replacement is due as much to a tendency of the replaced substance to go into solution as to a tendency of the replacing substance to go out of solution. Thus it may be said that the cause of precipitation is metasomatism.

Certainly the immediate walls of all fissures, joints, and zones

of strain are under different stress conditions than the more distant rock, for along those lines or surfaces of strain, stress has been relieved. Therefore, for all that is known at present, differential molar and molecular stress in those loci may be the prime cause of metasomatism. And the mechanism by which it operates may involve force of crystallization and some scheme of relative mineral stabilities under the peculiar local molecular conditions, a certain foreign substance in solution being utilized to replace an unstable molecule merely because of the abundant availability of the substance in solution. The rate of replacement would then be represented by a balance between the solubility and diffusivity of the substance being replaced, as against the availability of the replacing substance.

Precipitation being thus established within a field of diffusion, the diffusion gradient from the source of solution to the point of precipitation would be reduced to zero at that point. The flow of solute particles would be continuous to that point from all parts of the field of diffusion, either until the cause of precipitation ceases, or the supply of solute particles becomes exhausted through the completely efficient migration of the entire mass of solute to the point of precipitation.

In this manner, precipitation itself would be a cause of solution since by its operation, the field of diffusion becomes depleted in the solute, giving an opportunity for the substance at its source to pass continually into solution without reaching saturation; and the chemists tell us that all substances are soluble to greater or less degree.

Another and more potent cause of solution may be the existence of a metalliferous substance in (unstable) solid solution in some rock-forming mineral, such, for example, as copper, gold, mercury, or nickel in augite, many cases of which are to be found in the literature. In such an instance it might be reasonable to suppose that the metal in question would move from its place of confinement in the molecular structure of augite into an adjacent film of water because of the greater freedom and mobility of the metal in water. In fact this must be a consequence of the laws

of thermo-dynamics, which would require the solute to move from a point of less to a point of greater freedom.

An important auxiliary factor would be the previous or simultaneous existence in the water of another substance which might combine with the metalliferous one in question to make a more soluble compound. And still another potent auxiliary factor might be high differential compression, tending to reduce volume in certain loci or directions.

High temperatures and pressures would tend to increase solubility and diffusivity; and similar conditions must exist in the immediate neighborhood of magma chambers where steep heat gradients exist owing to the low conductivity of rock.

Water circulation may be invoked as an aid in migration wherever causes and open courses of circulation exist.

FACTORS IN ORE GENESIS.

Probably in a different catagory entirely from that of fissure-wall deposits, is the type of deposit in which there is a selective replacement of certain sedimentary beds or other formations. Detailed studies of such deposits seem to indicate that the metalliferous minerals have been precipitated about the peripheries of previously precipitated masses in such a manner as to suggest a contact reaction involving each mineral mass and its immediate rock walls. Wm. Ostwald [8] has pointed out that in the chemical laboratory, when a given salt is precipitated and left in the solution and container for a considerable time, the larger particles of precipitate grow at the expense of the smaller ones. The latter have larger surface area in comparison with their mass, thus giving the solution tendency the ascendency over the gravitative or aggregation tendency. If this principle is true for the laboratory, it probably also holds good in the rocks of the earth's crust.

In 1912, the writer formed nodular aggregations of pyrite crystals in kaolin, under atmospheric temperature and pressure, in the course of an experiment designed to demonstrate a method of formation of sulphide deposits within the vadose region of the

[8] "The Scientific Foundations of Analytical Chemistry," Ed. 1900, p. 22.

earth's crust by descending solutions.[9] The water solution, in the experiment, carrying pyrite in an oxidized state, flowed at the rate of one drop per minute through a horizontal glass tube two inches in diameter and half filled with well compacted, pure white kaolin, and kaolinite. In this clay bed were mixed a few weighed millimeter crystals of pyrite to serve as precipitation centers. In the course of five months pyrite nodules had been formed about the nest egg crystals; and two or three small ones had been formed entirely independently within the clay. In the paper describing the experiment it was not recognized that the chief factor controlling the precipitation, or at least the chief favorable condition, may have been diffusion. The clay being largely colloidal made diffusion easy.

In all probability, the formation of pyrite crystals and nodules in fault gouge, and in slate and shale beds, closely parallels the experiment just mentioned. In cases of this sort, where differential molar stress certainly is not a factor, considerable mystery surrounds the mechanism or mechanisms of precipitation, and displacement or replacement. Actual replacement is commonly clearly demonstrable in cases of the growth of pyrite crystals in slate beds where displacement may or may not have occurred. The pyrite crystals have usually taken their place without any disturbance of the fine laminae of slate. The diffusion gradient from the source of the guest mineral is reduced to zero at the point where precipitation is taking place; and that must be the cause of concentration of the mineral; but the mechanism of metasomatism operating about the periphery of the growing mass is a deep mystery. One can only surmise that the force of crystal growth[10] exerts a differential stress which results in the dissolution of the stressed molecules of the host substance.

If this category of ore deposits can be extended to include mineral bodies formed on dike walls and other contacts, then probably all cases of metasomatic orebodies will come under one or the other of the two general categories mentioned; and it may

[9] "The Vadose Synthesis of Pyrite," ECON. GEOL., vol. 8, No. 5, Aug., 1913.

[10] Stephen Taber in "Metasomatism and the Pressure of Growing Crystals," ECON. GEOL., vol. 21, No. 7, p. 717, 1926.

be that both of these will yield to a single explanation which solves the mechanism of replacement as involving differential molecular stress, force of crystallization, and concentration by diffusion. The crux of mineral concentration by diffusion lies in the cause of deposition or precipitation. The fact of a force of crystallization is not a theoretical matter but a matter of every day observation. If a crystalline mineral medium tends to grow by marginal accretion, it may be postulated to exert a force on its walls tending to deform their molecular structure. That may cause their solution and their replacement by the growing substances.

RESUMÉ

It must not be concluded from the foregoing paragraphs that diffusion is conjured as the genie of ore deposition. The argument is merely that this process functions as the principal agent of mobility in facilitating metasomatism. Also, that it may operate in many cases as the chief means of transportation of ore from points of origin to points of final concentration and fixation, leaving still a large part to be played by water circulation in certain cases where the water carrier of mineral is presumed to flow through really open channels, but is not supposed to pass through solid rock and sealed passages. When channels of circulation are closed, there can be no directive factor to guide circulation of mineral-bearing solutions through rock pores in sufficient quantity to produce ore deposits at certain points by replacement; but in such cases diffusion supplies a precise directive agency and a perfectly efficient agent of concentration effective through large radii in the vast lapses of geologic time available for ore-forming processes.

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GEOPHYSICAL METHODS APPLIED TO EXPLORATION AND GEOLOGIC MAPPING IN THE MICHIGAN COPPER DISTRICT.

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INTRODUCTION.

DURING the past few years such diverse mineral types as iron ore, copper sulphide deposits, gold veins, and oil pools either directly

[1] This paper is part of a discussion by the authors released for publication to the United States Geological Survey by James MacNaughton, President, Calumet & Hecla Consolidated Copper Co., and presented before the Society of Economic Geologists, Cleveland Meeting, December 30, 1927.

or indirectly, have been found as a result of the use of geophysical methods. The recent widespread interest in this subject is the outcome of the rapid development of the methods in the past decade particularly in Sweden, Germany, and France.

One type of geophysical observation has long been known and used in the Lake Superior region. Every geologist in the iron districts regards the magnetic dip needle as an essential part of his equipment, and a "magnetic survey" is usually one of the first steps in exploration. But curiously enough, the possibilities of magnetic methods were practically ignored in the copper country. It is safe to say that the present complete knowledge of the stratigraphy in this district could have been obtained at an enormous saving had magnetic surveying been used in the explorations of the old type. Thousands of feet of diamond drilling and trenching could have been dispensed with; preliminary shafts and crosscuts, poking around to "find the lode" would have been unnecessary; many miles of expensive transit work on the surface could have been saved; and mines such as the Ahmeek and Mohawk, long undiscovered because of a simple curvature in the strike, would have been found as soon as anyone with a dip needle had taken the trouble to work along the strike from the original discovery. However, the results were obtained even though at unnecessary expense and in most cases in a futile type of "cut and try" exploration which it is to be hoped will be indulged in less and less as time goes on and scientific principles of exploration are followed. The present problem is to decide what use to make of geophysical methods, having our present knowledge of the geology of the district. No very decisive results nor positive statements can be made in the following discussion of this subject. However, some experimental work and considerable study has been done on the use of these methods by the Calumet and Hecla Geological Department, and therefore we know something of the application of geophysical methods in this district.

Principles of Geophysical Methods.—All geophysical methods depend upon a contrast in the physical properties of the mineral deposit itself with those of the surrounding rock, or upon the dis-

covery or delineation by means of such contrasts of some geologic feature to which mineral deposits are related. Thus, magnetic deposits are more magnetic, massive chalcopyrite deposits are better conductors, and salt domes have a smaller gravitative attraction than the surrounding rock. Or a mineral body, itself undetectable, might be related to certain geological features which could be outlined by such methods. Thus, oil pools are discovered by outlining salt domes, hematite bodies by their relationship to magnetic dikes, or chalcopyrite deposits by their relationships to a certain contact. The essential condition in all geophysical work is that there be a detectable contrast in certain physical properties of the feature being sought, i.e., magnetic polarity, magnetic permeability, electrical polarity or conductivity, density, or elasticity, etc.

Three Applications of Geophysics.—There are three radically different methods of conducting geophysical investigations: (1) When the physical properties of the mineral deposits themselves have the necessary contrast with those of the country rock, then a method can be selected to locate directly the mineral deposits themselves. (2) It may be possible to take advantage of the physical properties of rocks associated with the mineral deposits, enabling structures known to be related to the mineral deposits to be determined or perhaps some accessory or gangue mineral of the ore deposits or of the surrounding zone of alteration may be detectable. (3) Geophysical methods may be used in general geologic mapping where the immediate objective is not so directly the location of mineral deposits as it is to build up a general geologic map which it is hoped will ultimately be of use in exploration.

The following discussion will take up in order these three points of view.

DIRECT APPLICATION OF GEOPHYSICS TO COPPER FINDING.

Existing Conditions.—There are two general types of copper deposits in the district, the so-called lode deposits, which are in amygdaloid or conglomerate, in most cases the former, and fissure

deposits. The fissure deposits are unimportant from the standpoint of production, having furnished less than 3 per cent. of the copper of the district. A satisfactory geophysical method must be sensitive enough to detect an amygdaloidal ore body having as little as 1 per cent. copper, and covered by a thickness of 30 feet or more of overburden. Thus it is apparent that the existing conditions are on the whole unfavorable; the desirable degree of contrast between the ore bodies and the unmineralized lodes is not present.[2]

The overburden of glacial drift varies from nothing up to some hundreds of feet. Inasmuch as the prospecting in the past eighty years has involved a thorough examination of the outcrops and the glacial drift, it follows that the majority of the undiscovered ore bodies are probably under rather deep overburden. But with geophysical, as with other methods applied on the surface, the deeper the overburden, the less the chance of ore discovery.

The ore bodies are tabular, and dip rather steeply, so that the outcrops although of great length are narrow, say from 10 to 20 feet on the average. They may vary in width from a few feet to 40 feet or more within a distance of 50 or 60 feet along the strike. Therefore the chances of discovery by a geophysical method are reduced, not only because of the average narrowness of the lodes, but also because the lines of observation may cross the lodes over the narrow spots. The conditions are very different from those in a district where the ore deposits are large, homogeneous, equidimensional bodies.

In most cases the copper is very irregular in both size and distribution. Some of it is microscopic, so fine that it gives a uniform pink tone to the including mineral, such as datolite or quartz. There are also intermediate particles, nuggets, sheets, and masses up to hundreds of pounds, in some cases thousands of pounds in weight. No physical continuity between the particles and masses exists to any degree. A possible exception to this is in the case of conglomerate ore, where the copper forms an interlacing

[2] The sole difference between a mineralized lode and many amygdaloids is that the former has 1 per cent. of its weight in native copper, which is 1/300 of its volume, whereas the latter have less copper.

cement in certain beds, probably in some places physically continuous over areas of some hundreds of square feet.

A very serious handicap to geophysical work in this district is the impossibility of making any exhaustive preliminary tests over known ore bodies. All of these have been worked from the surface downwards, and very little "back" or unstoped ground was left at the surface. Furthermore, in most places there is a maze of power lines, pipe lines, tracks, and other artificial conditions both on the surface and underground in the vicinity of the outcrops of the lodes which would give much stronger "geophysical" effects than the modest copper content of the lode itself. In one or two places in the district it has been possible to make rather dubious tests over shaft pillars and old backs, but these have been neither satisfactory nor convincing.

Thus, it seems unlikely that geophysical methods can be of direct use in exploration for copper deposits of the lode type. The fissure deposits, however, present much more favorable conditions for geophysical work, but, as pointed out, their small past production lends little incentive for exploration.

The most favorable consideration for electrical prospecting in this district is that the ore mineral is native copper, whose electrical conduction far excels that of the common sulphides. One wonders whether a one per cent. native copper ore would not be as easily detected by electrical methods as an ore carrying say 30 per cent. of chalcopyrite. Of the other common geophysical methods, the gravitometric and seismic have not been tried in lode exploration simply because the conditions in the district seem to offer no hope for success. The possibilities of the use of magnetic methods in the search for copper deposits have been considered in conjunction with magnetic observations made for various purposes, and this work is described in succeeding paragraphs.

ELECTRICAL METHODS.

Direct Conductivity and Resistance Methods.—Long before the development of the technique of the modern electrical prospecting methods, trials were made of the conductivity of the

copper bearing lodes. In 1893 Prof. James Fisher [3] measured the resistance of stretches of copper-bearing lode in the Quincy Mine and of the Eastern and Freda sandstones. Contact with the lode was made often by attaching the terminals to copper masses in the rock. The resistance was thus determined between points. About 1900, N. S. Osborne [4] did some work along equipotential lines for the E. J. Longyear Company both in the Lake Superior copper district and on the Mesabi iron range. Very variable and apparently inconsistent measurements were obtained and nothing of theoretical or practical importance resulted.[5]

Spontaneous Polarization.—This method depends upon the electrical currents set up at the outcrop of an ore body because of its chemical alteration in the zone of oxidation. Observations were taken across the Isle Royale lode and across the Kearsarge Amygdaloid and conglomerate lodes at Ahmeek by means of two movable electrodes, at a fixed distance apart, in contact with the ground. Traverses were made by shifting the electrodes along lines at right angles to the orebodies. The potential difference between the electrodes was determined at the different stations by means of a potentiometer in circuit with the electrodes. Absolutely no electrical effects were observed other than those due to the ordinary weak and irregular ground currents. While this was by no means a conclusive elimination of this method as of possible use in the district, it must be recognized that the rate of oxidation of native copper on which this method depends being very slow compared with the rate of oxidation of sulphide minerals, would therefore offer less chances for the method here.

Equipotential Lines.—This method depends upon the fact that if a current is sent through homogeneous ground between two electrodes the lines connecting the points having the same poten-

[3] Now of the Physics Department, Michigan College of Mines.

[4] At present with the U. S. Bureau of Standards.

[5] Mr. F. N. Bosson, Chief Electrical Engineer of the Calumet and Hecla Consolidated Copper Co., has found that it is possible in the deep salt water zones in the mines to operate electric trolley locomotives without the regular metallic ground return, the conductivity of the salt-water-soaked lode providing an adequate return circuit.

tial between and surrounding the electrodes are regular geometrical curves, of a character predeterminable by the theoretical considerations involved. If, however, a body of rock or ore having either higher or lower conductivity lies within the field between the electrodes, the points of equal potential do not lie along the regular theoretical curves of the homogeneous field, but the lines are found to be distorted in the vicinity of the body of different conductivity. If it is of lower conductivity than the surrounding rock, the equipotential lines are crowded together near it. If it is of higher conductivity, as most ore bodies are, the equipotential lines are spread apart over it and in its immediate vicinity.

A brief test of this method was made over the Isle Royale lode where it was assumed to be mineralized. While the lode itself appears to have distorted the equipotential lines, similar distortions were made by adjacent amygdaloids not known to be mineralized. It is felt that both the theoretical considerations and these experiments throw doubt on the possibilities of the successful use of this method in its present stage of development in the Michigan copper district. It is apparently able to indicate the locations of amygdaloids and would, therefore, be of use in general mapping of structure and stratigraphy, but it could not, however, compete with the quicker, simpler, and more economical magnetic methods.

Inductive Methods.—A loop of insulated wire is laid out on the ground, usually in a rectangular form. An alternating current provided by a generator or an induction coil operated with a storage battery, is sent through the loop. Thus a primary alternating magnetic field is set up within the loop of an ideal predeterminable shape if the ground is homogeneous. If a conductor (orebody) is in the field, however, the primary field of the loop sets up a secondary field about the conductor. This secondary field is opposed to the primary field and therefore causes a distortion of the ideal primary field above and near the conductor. By ingenious methods of amplification and observation of the electro-magnetic field within the loop, the secondary currents due to certain types of ore bodies can be recognized.

After some preliminary laboratory tests with specimens of rock and ore, the results of which were of an indifferent character, attempts were made to carry out practical investigations over the well-known Kearsarge, Pewabic, and Baltic amygdaloidal lodes, and the Calumet Conglomerate. All of these trials showed the copper-bearing lodes to give weak though detectable effects. The strongest of these were over the Calumet Conglomerate and the Pewabic Amygdaloid. After critical analysis, however, these tests were not as satisfactory as appeared at first sight. Dip needle readings were taken along the same sections on which the electrical traverses were run. The Kearsarge and Pewabic amygdaloids, and the Calumet Conglomerate showed varying degrees of magnetic disturbances in the vicinities of the lodes, and the electrical effects above the Kearsarge lode were definitely related to the magnetic anomalies rather than to the copper of the lode. The results of the tests at the Baltic and Champion mines, over the Baltic lode, were unsatisfactory because of thick overburden, rough topography, wire fences, and the fact that where the conditions were most favorable and weak electrical effects were obtained over the lode, similar effects were obtained away from the lode. The tests over the Pewabic lode may or may not be significant. Three mineralized lodes were indicated by the tests. It is possible that there are three mineralized lodes where the tests were made, inasmuch as mineralization in adjacent amygdaloids is a characteristic of the Pewabic orebody. Here again there were complications in the way of magnetism of the traps and possibilities of underground pipes, rails, etc. The conditions over the Pewabic lode were not such as to give a satisfactory test of this method.

The most satisfactory test was the one over the Calumet Conglomerate. Fortunately there was a shaft pillar two hundred feet wide at No. 12 shaft, Calumet and Hecla. The shaft itself was not in operation, there being no shaft house nor machinery at the surface. The overburden is about twenty feet deep, the copper content of the rock about two per cent., and the copper has the ramifying and connected form more common to conglomerate than to amygdaloid mineralization. The conditions for favorable

results were the best to be expected in lode mineralization in this district. Furthermore, while the adjacent traps showed some magnetic disturbance, the effects were not strong nor sudden. The results of the electrical tests, though weak, were the strongest obtained in the district, and were apparently due to the copper in the lode.[6]

These tests over known lodes indicated that under the most favorable conditions of copper content, copper distribution, lack of complicating factors such as strong magnetism in the traps, and thinness of overburden, the inductive method might detect an unknown copper-bearing lode. Furthermore, it was hoped that with additional work in the district the electrical prospecting experts might develop their methods to the greater refinement necessary for search for the Michigan type of copper deposit. Accordingly, the electrical prospectors were engaged for further field work. Exploratory crosscuts at shallow depths were being driven at the time on the lands of the LaSalle Copper Company, and those of the Cliff Mining Company. Seven and one half miles of double traverse were run at LaSalle and four miles at Cliff.[7] Some of these lines were run over the ground to be explored by the crosscuts. Dip needle readings were taken wherever electrical observations were made, and in many cases electrical effects were obtained, only to be eliminated from further consideration by finding that they were due to the local magnetism of the traps. This ability to eliminate electrical effects due to the magnetite in the rocks by such a simple and economical method was very fortunate. In order to make doubly sure that certain electrical effects were actually due to magnetite, the tes-

[6] The difficulty of detecting disseminated ore electrically is illustrated in Fig. 11 of a recent paper on geophysical prospecting; Mason, Dr. Max, "Geophysical Exploration for Ores," *Eng. and Min. Jour.*, vol. 124, No. 20, pp. 766–771; and No. 21, pp. 806–812, November, 1927.

[7] The traverse lines were run at right angles to the strike, and varied in length from a few thousands of feet up to three miles. Two parallel lines of observation 200 feet apart were run in each case. This was thought to be safer than a single line of observation because of the many variable conditions which might allow an ore shoot to give no effect in one spot, but a detectable effect not far distant. Thus these pairs of lines of observation are referred to as "double lines" or "double traverse."

timony of the dip needle was checked by digging a trench in one place where the electrical and dip needle curves both showed disturbances. As was expected, there was no copper in the amygdaloids exposed. Certain other electrical effects were apparently related to the water content of the overburden, weak disturbances being obtained where the traverse lines crossed over from dry sand to wet swampy soil. No electrical indications were obtained which were suspected of being related to a copper deposit. However, no copper deposits were found in the crosscuts through a part of the territory covered by the electrical work.

Conclusions.—Present indications are that the conditions existing in this district are distinctly unfavorable to the successful application of geophysical methods to the direct search for copper deposits. The electrical methods would seem to have the best chance of success and several of these have been given brief and inconclusive trials. The inductive method gave most encouragement. The present situation may be summarized as follows:

(1) The low grade of the deposits, erratic distribution of values, erratic variations in thickness of the lodes, which on the average are thin, lack of contrast in the conductivity of the ore and rock, depth and irregularities in depth of the overburden, the chances that the greater number of undiscovered lodes are in the regions of deeper overburden, the interference of magnetite in the traps, and the high water content of the amygdaloids, are all features which tend to make electrical prospecting difficult.

(2) There are practically no places in the district where conclusive tests of methods can be made over known ore bodies.

(3) Present electrical methods were developed chiefly to explore for massive sulphide deposits. Such deposits apparently give very much stronger and more definite results than the disseminated native copper deposits. Much greater refinement in technique seems to be necessary before these methods can be used with confidence in this district.

(4) Because of the weakness of the electrical effects which these copper deposits produce, other weak effects due to topographic roughness, small quantities of magnetite, irregularities

in ground water distribution, etc., which in massive sulphide districts are small compared with the electrical effects of the ore body, become of about the same order of magnitude as the effects due to the copper, and therefore lead to confusion.

(5) Too great a coincidence of favorable conditions seems to be required for positive results. The most satisfactory of the tests over known lodes was that over the Calumet Conglomerate, where the copper content was exceptionally high, the copper distribution exceptionally favorable, and the depth of overburden probably below the average.

(6) If it is true that such a coincidence of several favorable factors is required for a deposit to give a positive effect where the line of observation happens to cross it, then negative results do not go very far in condemning the ground explored by electrical methods.

(7) The encouraging features are, that the ore mined is native copper; that despite the fact that the methods have not been developed for the purpose of detecting such weak effects, trials over known ore where conditions are most favorable do give detectable though minute effects, and that the dip needle offers a rapid, inexpensive and simple means of eliminating one of the causes of uncertainty in the interpretation of electrical effects.

(8) Too little is known at present to form a final opinion as to the possibilities of electrical prospecting for native copper deposits. It is felt that there is enough of a chance of successful adaptation to the conditions of the district to warrant further research being carried on by men uninterested in the commercialization of any particular method; and the mining companies should not be expected to pay the same fees for such experimental work as for a method whose success has been demonstrated with ore bodies of this type. A federal government or state organization should handle the experimental work. At any rate as experience is gained in the practice of the methods elsewhere, the tendency will undoubtedly be to become more and more expert in the detection and interpretation of the weaker effects due to

lean disseminated deposits, thus approaching a solution of the problem of this district.[8]

INDIRECT APPLICATION OF GEOPHYSICS TO COPPER FINDING.

If the copper deposits had associated alteration zones, or were related to folds, fissures, faults, unconformities, or contacts, that could be detected by geophysical methods, then such features would be of indirect use in the search for the deposits. But magnetic work thus far accomplished indicates that the deflections in the vicinity of the copper deposits are simply due to the primary magnetite of the original rocks and in no way related to the copper deposits. Similarly no structural relationships such as those suggested above are known to exist. Therefore, existing knowledge indicates that there is no present possibility of applying geophysics in this indirect manner. So far as now known, the only such application of geophysics likely to arise would be the tracing of the lateral extensions of a new deposit by tracing the strike of the lode in which it lies with the dip needle or by some similar means.

APPLICATION OF GEOPHYSICAL METHODS TO GEOLOGIC MAPPING.

Early Geologic Work.

Early in the history of the district fair geological maps were made by tracing trap and conglomerate ridges, enabling general

[8] No attempt has been made in this discussion to present the technical side of geophysical prospecting. Some of the more important papers on the subject in the English language are listed at the close of the articles by Lundberg, Hans, "Practical Points on Electrical Prospecting for Location of Mineral Deposits," *Min. Cong. Jour.*, vol. 12, No. 12, pp. 737–738, October, 1926, and by Barton, D. C., "Applied Geophysical Methods in America," ECON. GEOL., vol. 22, No. 7, pp. 649–668, November, 1927.

We wish to acknowledge the assistance and coöperation of the experts in electrical prospecting who worked with us in what we regard as a piece of economic research. Without their technical skill and apparatus we could not have carried on the work. The experts who were in the district were Sherwin F. Kelly, who tried out the Schlumberger methods, and Ingemar Tennberg, who, with his assistant, Mr. Roxtrom, both of the Swedish American Prospecting Corporation, tried out certain of the Swedish methods. In fairness to these gentlemen it should be stated that they regard the possibilities of their respective methods somewhat more optimistically than we state them in the foregoing discussion.

correlations of certain horizons to be made, and the general structure to be determined. As one after another of the lode deposits were discovered, the idea took hold and still persists, that there were a few "master lodes" that extend the length of the district. The object of the explorers was to locate these "master lodes," the Isle Royale, or the Pewabic, or the Calumet Conglomerate, and the others, on their particular property. This was a matter of mapping, and therefore great efforts were made to get the stratigraphic relationship of these beds to the more easily traceable key horizons. Thus there followed a period of trenching based upon accurate surveying, to trace the lodes from one end of the district to the other. Diamond drilling was utilized to determine the stratigraphy, and perhaps one million feet of boring gave a detailed knowledge of the stratigraphy, but no new ore bodies.[9]

While all this work was going on in search of the "master lodes" in the copper district, just a few miles south, in the iron districts, magnetic instruments were being used not only in locating iron deposits but in tracing magnetic horizons. Magnetism in the rocks of the copper district was noted on the plats of the original land survey, and in 1873 Brooks published an account of the use of magnetic observations in the Michigan iron districts.[10]

It is certain that the same knowledge of the structure and stratigraphy of the district could have been obtained much more economically had the dip needle been used in conjunction with the other methods, as many of the holes and shafts would never have been put down, or would have been more accurately located

Ideal Conditions for Magnetic Work.

Magnetic Contrasts.—While gravitative, seismic, and electrical methods would undoubtedly serve to determine the geologic structure, the conditions for mapping by means of magnetic observations are so favorable as to exclude the others. The interbedded flows and conglomerates, many of them extending along

[9] With the possible exception of the Lake lode, which produced about seven million pounds of copper before it was forced to shut down.

[10] Brooks, T. B., Geol. Survey of Michigan, part 1, vol 1, pp. 205–243.

the strike for tens of miles, have magnetite in varying quantities and so provide the necessary contrasts in adjacent rock bodies. This contrast causes distortions in the earth's magnetic field, and there are various instruments which can detect them.

Simplicity of Geologic Structure.—Since in many cases the magnetite content of a certain bed is characteristic, it is possible to trace individual beds for miles by simple magnetic observations. Furthermore, the beds are parallel, so that once a positive correlation is established, vague features in the near-by parts of the section, if they " line up " with the established correlation, can be related to other definite horizons with much more certainty than would be possible with complex structures. This makes the interpretation of most of the magnetic data very simple.

Frequent Geologic Checks Available.—One who undertakes reconnaissance magnetic work and crosses the mineral belt at regular intervals, can tell where he is geologically, at least over the greater part of the district. It is possible in most places to tie in to known geologic features frequently, because of diamond drill sections and extensive explorations. The question immediately arises as to why, if the geology is so well known, one should undertake extensive magnetic mapping. This is indeed debatable, and it will be considered throughout this discussion. The point to be made here is that if magnetic surveying is carried on, the existing knowledge of the district is sufficient to enable a close coördination between magnetic effects and known geology to be maintained during the work.

Favorable Geographic and Topographic Conditions.—The country is well adapted to rapid methods of magnetic surveying. The copper-bearing formation as a whole is a long narrow belt, well served by roads and railways. Over the greater part of the district a complete dip needle traverse of the formation can be laid out at any place and completed within a few days. Frequent section corners, roads, diamond drill holes and mine shafts, provide convenient tie-ins. A topographic map of the U. S. Geological Survey is available over that portion of the district extending from Cliff to Globe.

Theory and Practice of Magnetic Surveying.

Fundamental Principles.—Over areas underlain by magnetically homogeneous rock material, the earth's magnetic field is essentially uniform, the lines of magnetic force having a uniform inclination and spacing, *i.e.*, the magnetic field is uniform in direction and intensity. If a rock of different magnetic permeability lies within the otherwise magnetically homogenous area, the normal earth's field is then distorted. The lines of force are steepened or flattened and are crowded together or spread out, giving local variations in the direction and intensity of the earth's field. Mapping geology by means of magnetic instruments, herein referred to as "magnetic surveying" simply involves the detection, tracing and geologic interpretation of these local variations or anomalies in the earth's magnetic field.

Instruments.—There is a variety of instruments designed for this purpose. An ordinary compass may serve to detect variations in the direction of the horizontal component of the earth's field if several readings are taken while walking along a straight line. Compasses equipped with sundials are used to determine the true meridian at a given station, the deviation of the horizontal component of the earth's field, or the declination being observed by reading the angle between the meridian and the position of the compass needle. The period of vibration of the needle from place to place can be determined and a measure of the variations in the horizontal intensity of the earth's field thereby obtained.

The most useful all-round instrument for magnetic surveying from the standpoints of simplicity, easy repair and adjustment, lightness in weight, sensitiveness, rapidity in taking observations, and satisfactory results, is the dip needle. Essentially, it is a magnetized needle which swings in a vertical plane about a horizontal axis with an adjustable counterweight on one end. In the Lake Superior district the needles are adjusted to come to rest in nearly a horizontal position in the normal field. In making an observation, the magnetic meridian is first determined by using the dip needle in the horizontal position, as with an ordinary compass. It is then tilted vertically, leveled by means of

a bubble, and the deflection of the needle from the horizontal read in degrees. One who standardizes this procedure can make and record a dip needle observation in 30 seconds.

More complicated and more sensitive instruments for making magnetic observations are available. There are various types of magnetometers for instance which determine all the elements of direction and intensity. As compared with the dip needle however, the additional delicacy and refinement of the results yielded by such instruments in ordinary work do not compensate for the clumsiness, need of transit surveys for locations of observation stations, liability to damage, difficulty in repairing, and the time consumed in preparing for and making observations, most or all of which are disadvantages of the various magnetometers.

Plotting of Results.—There are various methods of plotting dip needle readings. In some cases a magnetic contour map is made by connecting points on the map which give the same dip needle variations. Another method is to lay out the line of traverse on the map and plot a profile of the dip needle readings from it as a base.

History of Work in the Lake Superior Keweenawan.

Early Observations.—The earliest records of the observation of magnetic variations are those made at the time of the original land surveys. Some of these are noted on the township plats. While the land survey was still in progress, geological work by Jackson and his assistants was being carried on, and some attempt was made to find out whether there was any relationship between the copper deposits and the magnetic anomalies.[11] This work was not brought to a conclusion.

Recent Work.—During the many years in which systematic magnetic surveying has been carried on in the iron districts, occasional traverses were made, intentionally or unintentionally in areas underlain by Keweenawan traps. Magnetic lines of attraction, supposedly due to iron-bearing formation, have been

[11] Jackson, C. T., "Report of the Geological and Mineralogical Survey of the Mineral Lands of the United States in the State of Michigan," U. S. 31st Cong., 1st sess., S. Ex. Doc. 1, pt. 3, and H. Ex. Doc. 5, pt. 3: 586–605 (1849).

followed, which after investigation by diamond drilling or otherwise have been found to be related to lava flows.

In recent years the state geological surveys of Minnesota and Wisconsin have conducted systematic investigations of the Keweenawan igneous rocks using magnetic observations as one of the means of mapping the geology. So far neither organization has published a formal report of the work although preliminary papers have been written, briefly presenting some of the results.[12] The magnetic work in the Minnesota Keweenawan was largely in the area of the great Keweenawan intrusive, the Duluth Gabbro. Enough work was done over the traps to the south of the gabbro to show that there were horizons of strong magnetic attraction in those beds. In more recent years the Minnesota survey has done some magnetic work in the Keweenawan lavas, but it was more or less incidental to other projects and has not been made the object of serious investigation.

By far the most comprehensive magnetic surveying in the Keweenawan has been done by the Wisconsin Geological and Natural History Survey by field parties under the immediate supervision of H. R. Aldrich. This work was started by W. O. Hotchkiss, at that time Director of the Survey, in 1922, and has been carried on by Mr. Aldrich from the beginning to the present time. Many hundreds of square miles of drift covered Keweenawan are being mapped structurally and stratigraphically by magnetic methods. The occasional outcrops are thus placed in their true relationship to each other, and faults, folds, formation boundaries, unconformities, and individual beds are being mapped largely by magnetic methods. A few diamond drill sections are available, and these together with occasional good exposures of the section along streams, enable the observers to tie in the magnetic features to the geology from time to time. With the possible exception of the land classification work over possible

[12] Broderick, T. M., "The Relation of the Titaniferous Magnetite of Northeastern Minnesota to the Duluth Gabbro," ECON. GEOL., vol. 12, pp. 663–696, 1917. "Some Features of Magnetic Surveys of the Magnetite Deposits of the Duluth Gabbro," ECON. GEOL., vol. 13, pp. 35–49, 1918. Aldrich, H. R., "Magnetic Surveying on the Copper-Bearing Rocks of Wisconsin," ECON. GEOL., vol. 18, pp. 562–574, 1923.

iron-bearing lands, made by the same organization,[13] this is the most comprehensive magnetic survey ever made, so far as the writers are aware, with no immediate application to ore finding as a direct objective. However, there are no theoretical reasons why important copper deposits should not exist in Wisconsin as well as in Michigan, except the fact that they have been found in Michigan and not in Wisconsin. The members of the Wisconsin Geological Survey believe that "The areas away from Keweenaw Point may perhaps at once come in for new examination, but we feel that if not at present the attention will come within a very few years. . . . Then the question comes, if the exposures are so meager and if the drift cover is so deep that geologists in the past have not been able to obtain the data necessary for a final conclusive opinion, what can a geologist do in such an area? So far as a thorough examination and testing of the rock is concerned, we of the Survey fully agree that ordinary methods hold out little hope for an immediate solution of the problem. But we believe that there is much that may be done on the surface by means of a magnetic survey that will aid campaigns for the systematic disclosure of what lies below the drift. . . ."[14]

Besides this magnetic work on the Keweenawan, magnetic observations have been made in recent years within the Michigan copper district itself, the results of which will form the basis of the following discussion.

Recent Work Within the Copper District.

The writers have no knowledge of any systematic magnetic work having been done in the Michigan copper district between that at the time of Jackson and the present work by the Calumet and Hecla geological department. This department has carried on some magnetic work at three different periods with as many different purposes in view. The purposes and general results of the work in these periods are briefly as follows.

Work Previous to 1925.—When the special geologic survey

[13] Hotchkiss, W. O. (and others), "Mineral Land Classification Showing Indications of Iron Formation," Wis. Geol. Surv. Bull. 44, 1915.

[14] H. R. Aldrich, *op. cit.*, p. 574.

of the Calumet and Hecla Mining Company was started in 1920, it was necessary to make some sort of tentative decisions as to the lines of research to be taken up first. The statements found in the literature that copper-bearing lodes caused magnetic disturbances were of course a challenge, and some observations were made with the dip needle in 1920 to check this statement. As a result of these observations and those made at a later date for the same purpose, it was decided that there were no obvious magnetic peculiarities in the vicinity of the copper deposits which could be detected by ordinary dip needle practice in the light of present knowledge. Magnetic traverses have been run across the Calumet Conglomerate and the Kearsarge, Pewabic, and Baltic amygdaloid ore bodies. The brief magnetic work of the first summer likewise demonstrated the possibility of tracing the strike of certain beds by their magnetic characteristics.

Work in 1925.—The magnetic work done in 1925 was for the specific purpose of eliminating effects which were due to magnetite of the traps and sediments from further consideration in the study of the results of electrical prospecting. The location of the magnetic traverses and observations coincided with the location of the electrical traverses and observations. All of this work was in what may be termed the productive mineral belt. The observations were spaced 30 feet apart along surveyed lines at right angles to the strike. The results of this dip needle work in eliminating electrical effects due to the magnetite of the rocks were most satisfactory. The observations made at this time also furnish data of use in the study of the possibilities of magnetic work in structural and stratigraphic geology.

Work in 1926.—As a preliminary to exploratory work about to be started in Keweenaw County, it was decided for various reasons to carry on some magnetic work. The data so obtained added to that of previous years forms the basis of the following discussion of the application of magnetic methods to structural and stratigraphic mapping in this district.

Results.

Determination of Strike.—One of the most simple and easily obtainable deductions by means of magnetic work is the local strike. A magnetic horizon is picked up and crossed at suitable intervals, and the line connecting that particular feature from section to section is the strike of the bed which causes it. It is desirable to know the strike in diamond drilling and in inclined shaft sinking. There are numerous examples of diamond drill holes which would have been pointed differently and would have yielded more satisfactory information had the strike been known. Examples of shafts which would have been sunk differently had the strike been known are the Lake No. 1 and the New Baltic shaft near the Keweenaw Fault.

Tracing Specific Horizons.—In earlier days, when certain lodes were known to be mineralized in different places, it was desirable to find the lateral extensions of the ore bodies not only on the same properties where development was going on, but on adjacent properties. This involved first, tracing the strike of the lode itself, by trenching, surveying, diamond drilling, pit or shaft sinking, followed by crosscutting or by a combination of these methods. In many cases this could have been done at a small fraction of the expense and time by dip needle work by determining the horizontal distance from the lode to one or more near-by magnetic horizons, tracing these horizons with the dip needle onto adjacent ground and then measuring back to the position of the lode.

Location of Faults, Folds, and Fissures.—Folds in the formation can be easily determined by magnetic methods, the magnetic lines following the curvature of the bedding. Similarly faults can be located by offsets in the magnetic lines, although in some cases the magnetic lines do not extend right up to the fault plane, probably because the magnetite has been altered in the crushed zones of the faults. Such alteration suggests the possibility of locating fissures to be explored for copper deposits. Magnetic methods would probably have been of great aid in solving the structural problems where there are local complications, especially

near the Keweenaw Fault. Such areas are present at Mayflower-Old Colony, New Arcadian, Lake, and elsewhere. The possibility that these areas are too close to the Keneenaw Fault to yield traceable lines of magnetic attraction would make magnetic work of no avail, but so far as the writers are aware, magnetic methods have not been tried in these places.

Other Relationships of Magnetic Features to Geologic Features.—The dip needle profiles of the copper-bearing series show certain recurring features, the recognition of which is of importance because they are the bases of correlation from one section to another. There are long stretches where the curve is essentially flat and without character, other stretches where the curve is rough, due to closely spaced areas of high, low, and normal attraction, other areas where the curve is a broad sag or an arch, and still others where the curve though rough in detail is in a broad way a succession of sharp rises, gradually falling back to normal. The latter feature Aldrich likens to the teeth of a ripsaw.[15] The underlying cause of the varying magnetic field is the unequal primary distribution of magnetite in the inclined traps and sediments. In some cases this is related to differences in the magnetite content of successive flows. There are several types of extrusive rocks, varying chemically, mineralogically, and texturally. They range in composition from rather acidic felsites to the more basic members of the basalt group, and vary widely in their magnetite content. Unequal distribution of magnetite is also the result of the unequal thickness of the flows. In general the thicker flows give the stronger magnetic effects. This is probably in part due to the fact that the slower cooling of the thicker flows allows a more complete segregation of the magnetite to occur, and that therefore a flow of a thickness of say two hundred feet would have a greater magnetite concentration than five flows of the same composition, each but forty feet in thickness. In general the thicker ophites seem to cause the stronger magnetic effects.

Local alterations, none of them so far recognized as being related to copper mineralization, have destroyed some of the

[15] *Op. cit.*, p. 566.

primary magnetite, thus causing erratic distribution. For example, the oxidation of the ferrous iron, that started perhaps as soon as each flow reached the surface and continued throughout the period of crystallization and even later. Thus there is very little magnetite left in the amygdaloidal tops of the flows and the crystals of magnetite and other ferrous iron minerals deep within the flows are replaced to varying degrees by hematite. Even more erratic is the alteration of the magnetite in the vicinity of the faults and fissures. Little is known about this at present, but there are strong indications that it exists. For instance, the traverses which crossed the thick Greenstone flow in Keweenaw County along the roads through the big gaps caused by fissure zones show flat magnetic curves while those that crossed at Ojibway and North American away from any known fault or fissure zones show violent magnetic effects in the Greenstone area.

Finally, there is the masking effect of the overburden and to some extent of the topography. In general, the thinner the overburden the more ragged the dip needle curve, the effect of the overburden being to smooth out and generalize the curve.

Abrupt changes in topography modify the magnetic curves to some degree, and in places the varying thickness of drift together with abrupt topographic changes may tend to make the correlation of geological horizons with their related magnetic effects somewhat difficult.

Persistence of Magnetic Features.—The value of magnetic work in geologic mapping is dependent upon the persistency of the magnetic properties of individual beds. If the concentrations of magnetite in a single bed were haphazard, there would be no magnetic lines parallel to the strike or to any other feature and therefore the magnetic observations would be useless. This, of course, is not the case. The magnetite concentrations are characteristic of geologic horizons. Some of them are much more persistent than others, however, just as are the flows themselves. Some magnetic effects can be followed for many miles, others for but a few hundred feet. The magnetic attraction at about the horizon of the Ashbed is well marked in five out of the six

sections that cross it in Keweenaw County. It is also present many miles to the south in the LaSalle area. This is an example of a very persistent and dependable magnetic line. Another persistent magnetic line is found about 1,300 feet horizontally above the Ashbed in Keweenaw County. In general, the closer the traverses the greater the number of possible magnetic correlations. The double traverse lines 200 feet apart in the LaSalle area show in most places practically parallel magnetic curves, and correlations between them can be drawn at hundred foot intervals or less in places. The distances between pairs is about one-half mile, and the number of possible correlations between pairs is much less than between the two curves making each pair. In Keweenaw County, where the distance between traverses is still greater, the number of reasonable magnetic correlations is correspondingly less. The experience in correlating between diamond drill sections is the same. Where the drill sections are closely spaced more correlations can be made from hole to hole than where they are widely spaced. The flows thin out and disappear, and as a result the corresponding magnetic lines become weaker and disappear. Where one flow wedges out and is replaced along the strike by another flow, the two are in most cases of the same petrographic type. This means that the flows outpouring in the same stages of the igneous activity were of a similar character. Thus there are portions of the section characterized by glomeroporphyrites, others are characterized by ophites, and still others by intermediate types. The changes from one rock type to another are not abrupt, for there are in most places several flows of an intermediate type between the two extremes. The point to be considered here is to what extent this persistence of the belts of flows (in spite of the lack of persistence of the individual flows within the belts) is reflected in the magnetic profiles. In general it may be said that the persistence of magnetic effects bears a close relationship to the persistence of the geological horizons which cause them. A given magnetic line probably weakens and disappears as the flow which causes it thins and wedges out. The broad general features of the magnetic profiles related to the groups of flows of the various types are

more persistent, just as the groups are more persistent than the individual flows of which they consist. Mr. Aldrich [16] inferred this wedging out of individual flows and the existence and persistence of the belts of flows of similar composition in the Wisconsin Keweenawan, almost solely from the behavior of the details and broad features of his magnetic profiles.

Magnetic Correlations.—The foregoing discussion will enable the reader to appreciate the many variables to be considered in the interpretation of magnetic observations in terms of stratigraphy and structure. The first step in this interpretation is to correlate the magnetic features of two or more adjacent cross traverses. The next step is to correlate the magnetic features with the local geology; to tie up certain magnetic lines with the formations which cause them, and to relate broad magnetic features to similarly broad geologic features. Finally, working from areas where the geology is well known to areas where the geology is less certain, the determination of the geology from the magnetics becomes possible.

PRESENT ATTITUDE TOWARD MAGNETIC SURVEYING.

As a result of this study of the application of magnetic methods to the geological problems in this district, certain conclusions have been reached, which are, of course, not to be regarded as final. They are as follows:

(1) There is no reason to hope that copper ore bodies in amygdaloids and conglomerates can be detected by magnetic methods. There is no feature of magnetite distribution known to be in any way related to the presence of the copper. There may be a zone of alteration adjacent to fissures and faults in which some of the magnetite has been destroyed. Some of these may be mineralized, and it is conceivable that a search for fissure deposits in drift covered country might be aided by magnetic surveying.

(2) Magnetic methods are of use in the preliminary stages of the exploration of specific areas. Dip needle traverses across the

[16] *Op. cit.*, p. 568.

formation at closely spaced intervals give a great amount of detailed information concerning the geology. The strike, presence of faults with amount of offset, a general idea of the thickness and character of the traps, and some idea of the thickness of overburden can be obtained. For this purpose the traverses should be at intervals of not more than one quarter mile, and more closely spaced where any structural complications develop. Readings should be taken at about 25-foot intervals along the traverses.

(3) Where it is desirable to trace the strike of a specific lode, magnetic methods will ordinarily serve. A traverse should be run across the formations where the position of the lode is known, thus determining its relationship to the near-by magnetic horizons. Then parallel traverses are made at intervals working into the area where the position of the lode is to be traced, the lode being located by its determined position with respect to the magnetics.

(4) Magnetic methods should help in solving local structural problems such as faulting, or pitching synclines and anticlines such as occur at the Lake and the New Arcadian mines.

(5) Since the beginning of geological work in the district, emphasis has been placed upon detailed stratigraphy. As a result the stratigraphy is especially well known. Individual conglomerates and traps have been traced over fifty miles along the strike. The character of the beds in the different parts of the section is known from one end of the district to the other. All of this detailed information has been obtained by surface mapping, diamond drilling, and underground openings. There are some places in the district, of course, where the structure and stratigraphy are less well known, as south of Victoria and east of Mandan, where the next step in stratigraphic and structural mapping might well be accomplished by a magnetic survey. Anyone who would enter into such a project should, of course, be convinced of its justification on the basis of its scientific or economic importance. It would be of considerable scientific interest to map the geology from the Victoria mine to the Wisconsin line, thus connecting in greater detail the geology of the copper district with that of the Wisconsin Keweenawan, now being mapped by the Wisconsin

Geological Survey. Such a project would be especially valuable to the State of Wisconsin because it would enable an interpretation of the Wisconsin geology to be made more closely in terms of the geology of the copper producing portions of the Keweenawan series.

So far as the part of the district between Victoria and Mandan is concerned, general magnetic mapping is less attractive, since geologic maps already in existence are fairly detailed and accurate. In other words, the magnetic surveyor would start in this district with a map of more detail and greater accuracy than he could hope to finish his work with in the Wisconsin Keweenawan. A certain amount of magnetic work in such well mapped areas would be of use, however, in gaining an understanding of how the various magnetic effects should be interpreted. Then when magnetic data from large unexplored drift covered areas, such as the Wisconsin, are studied, a much greater degree of certainly in their geologic interpretation would be possible.

CALUMET, MICHIGAN.

THE COPPER PROSPECT AT BARRIO PASTO, PORTO RICO.[1]

R. J. COLONY AND H. A. MEYERHOFF.

COPPER has been reported in Porto Rico from several localities, of which only three have shown sufficient mineralization for serious prospecting. Among those which have at least aroused local interest are the following (Fig. 1):

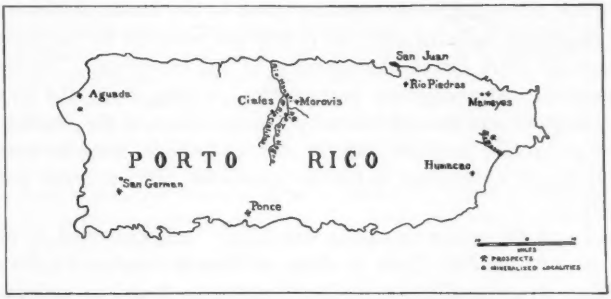

FIG. 1. Location map of Porto Rico.

(1) A prospect two and one half miles south of Aguada at the west end of the island, where, according to Hubbard,[2] native copper and products of oxidation occur in crush-zones of an

[1] The authors are indebted to the New York Academy of Sciences for the opportunity to make a study of the material covered in this report and for permission to publish the results of the special investigation in advance of the report on the geology of the Arecibo District, which has been studied by the junior author. On the property every courtesy was shown by Mr. G. A. Schulte and Mr. V. A. Menaglia, who aided materially in the collection of data and specimens.

[2] Hubbard, Bela, "Geology of the Lares District, Porto Rico. Scientific Survey or Porto Rico and the Virgin Islands," *N. Y. Acad. of Sci.*, vol. II, 1923, pp. 105–108.

augite andesite, and where some exploration and mining have been undertaken. (2) A prospect north of San German, which is mentioned by Mitchell,[3] but which he was unable to locate. (3) Several small openings along Rio Toro Negro and Rio Cialitos, south of Ciales, mentioned, but not described, by Semmes.[4] (4) A mine in Barrio Pasto, southwest of Morovis, which is the subject of this paper.[5] (5) A mineralized locality at kilometer 31.1 on the Rio Piedras-Humacao road, not far from the village of Mameyes in the northeastern portion of the island. In this locality the oxidation of sulphides deposited in fractures in andesite porphyry is indicated by strong malachite coloration in a cut on the roadside. (6) An abandoned mine above the valley of Rio Blanco at the southeastern margin of the Luquillo Mountains, which, according to information given by Sr. David Noble, was opened and operated until the destruction wrought by the hurricane of 1898 forced abandonment of the workings. This deposit proved completely inaccessible; judging from the local geology it was formed either by mineralization in the fractures of an andesite porphyry country-rock, or by replacement in dense calcareous Cretaceous sediments associated with andesite porphyry.

In all the copper prospects which have been examined in the course of the New York Academy of Science's survey of Porto Rico, the mineralization has been invariably found in andesitic flows or shallow intrusives, and usually in crush- or fracture-zones in rocks of these types. The occurrence at Barrio Pasto is characteristic in its origin and associationships; and as the outcome of an excellent opportunity to study its geology and mineralization in a series of fresh exposures, this paper is offered.

The copper prospect at Barrio Pasto is located slightly north of the geographical center of Porto Rico, about four miles southwest

[3] Mitchell, G. J., "Geology of the Ponce District, Porto Rico, Scientific Survey of Porto Rico and the Virgin Islands," *N. Y. Acad. of Sci.*, vol. I, 1922, pp. 294–295.

[4] Semmes, D. R., "Geology of the San Juan District, Porto Rico. Scientific Survey of Porto Rico and the Virgin Islands," *N. Y. Acad. of Sci.* vol. I, 1919, p. 104.

[5] *Ibid.*, pp. 104–105.

of Morovis and about an equal distance south-southeast of Ciales (Fig. 1). It is situated in an area of late Cretaceous rocks which have been mapped by D. R. Semmes[6] as andesite porphyry. The prospect was described briefly by Semmes, who at the time of his visit in 1915 found the openings almost completely buried beneath rock debris and dense vegetation. The information which he gives about the mineral deposit is thus brief and not wholly complete. He describes it as follows[7]:

> The country rock is an andesite porphyry. . . . This porphyry occurs as a large intrusive extending out of the district on the west. In this intrusive the ore occurs as impregnations along cracks and fractures. Several of the prospects in this vicinity have been partially explored. The principal one was examined by an American mining company, and one shipment of several tons was sent to the States for smelting. In this prospect the principal vein or impregnated zone is about four feet wide. This has been followed about 30 feet into the hill. It is intersected by several other similar veins of small size. It is evident that the porphyry has been fractured and subsequently was mineralized. The copper-bearing waters have followed these fractures and deposited in them the copper minerals, impregnating the neighboring porphyry for distances varying from a few inches to several feet. At the juncture of two of these mineralized fractures quite a showing of copper is developed. In the specimens collected malachite, chrysocolla, and azurite appear in the greatest abundance. Cuprite and chalcocite are rare at the surface, but may prove more abundant in depth.

In the course of the geological survey of the Arecibo District during the summer of 1926, Barrio Pasto, which lies along the eastern boundary of the district, was revisited. At the same time two Americans, one of them interested in the mining property, the other a mining engineer, had come to study the mineralized area and to reopen it if conditions warranted. Thanks to the courtesy of these two men (Mr. G. A. Schulte and Mr. Victor A. Menaglia), an opportunity was presented for the examination of the entire property after it had been cleared, and after fresh cuts had been exposed by blasting.

General Geology.—The geologic features in the immediate vi-

[6] Semmes, D. R., *op. cit.*, geologic map.
[7] *Ibid.*, pp. 104–105.

cinity of operations proved to be exactly as Semmes had described them. The country-rock is an augite andesite which has been considerably fractured along a relatively narrow zone. Mineralization has taken place along the fractures and is greatest where two or more of them intersect. The crush-zone formed by the fracturing has acted as a zone of weakness, and gullying has taken place along it. All of the copper found on the property is restricted to the sides of the ravine at elevations ranging between 1,000 and 1,300 feet. The ore includes primary and secondary sulphides and oxidation products, and, although it is rich at joint intersections, these are too widely spaced for economic exploitation. The quantity of ore, moreover, is small, and to judge from the local character of the deposit there is no assurance that it continues in depth.

The geology of the region surrounding the mine is more complex than Semmes's description and geologic map indicate. The

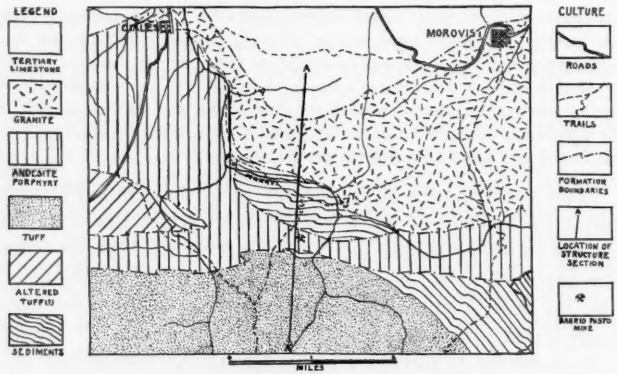

FIG. 2. Geology in the Barrio Pasto District.

andesite porphyry is not a large stock-like intrusion, but is rather a narrow apophysis more nearly resembling a thick, irregular dike, which cuts across the structures of the surrounding sedimentary country-rock (Fig. 2). Beginning at Morovis on the

north the following geologic section is encountered (Fig. 3): A broad stock of granite extends from the base of the Tertiary

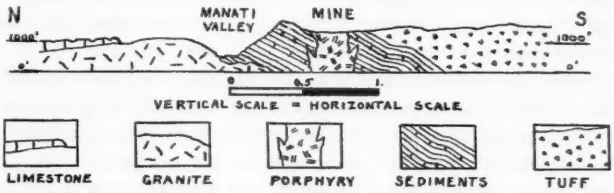

FIG. 3. Structure section across Barrio Pasto.

cuesta to the valley of Rio Manati, whose course at this point follows roughly the southern margin of the intrusive. The southern wall of the valley is composed of a series of highly folded sediments, in which tuffaceous shale and thin-bedded limestones are the dominant types. The structure is variable; where most persistent the strike is south 80–85 degrees west, and the variable dip averages about 30 degrees south. Sedimentary rocks predominate from the valley southward to a point within 200 yards of the mineralized area, and there give place to the porphyritic intrusion, in which occasional sedimentary xenoliths are found. Whether or not the presence of the sediments had any causal connection with the mineralization was not established, but they appear to have exerted some control over the distribution of the porphyry. Deposition of the ore seems to have been conditioned in large part, if not wholly, by the development of shrinkage fractures within the igneous body, permitting circulation of the mineralizing solutions. Immediately south of the mine the rock-section changes to a series of massive tuffs and other volcanic fragmentals, in which intrusions are absent.

Relation between Ore and Physiography.—The region in which the mine is located rises to an upland peneplane with an average elevation of 1,600–1,700 feet. This erosional surface, which has been named the Caguana peneplane,[8] has been deeply dissected

[8] Meyerhoff, H. A., "Tertiary Physiographic Development of Porto Rico and the Virgin Islands," *Bulletin, Geol. Soc. of Amer.*, vol. 38, 1927, pp. 560–562, 567–572.

by Rio Manati and its tributaries, the dissection along the main streams amounting to as much as 1,200 feet. Field studies have shown that the Caguana peneplane was uplifted at the close of the Pliocene and that the dissection which has taken place occurred entirely in the Pleistocene and Recent.

When the ore-body was examined, it was postulated that the physiographic history of the region might afford an explanation of the intimate association of primary and secondary sulphides and oxidation products. Although similar associationships are common in many mineral deposits, the comparatively late date of uplift, which amounts to 1,500 feet in the Barrio Pasto area, with a concomitant lowering of the water-table, was regarded as a possible reason why supergene processes had not yet completely

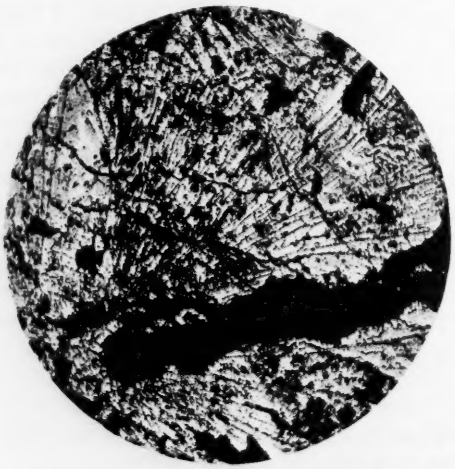

FIG. 4. Colorless radiate mineral in the crush-zone breccia. Its optical properties correspond to those of prehnite; it occurs both in fragments of partially silicated limestone and in andesite fragments that comprise the breccia, and is consequently associated with and replaced by the ore. Ordinary light, × 35.

converted the primary and secondary sulphides, stranded high above the water-table, into the normal products of oxidation that

characterize the zone of weathering. Obviously the problem is intimately related to other factors which tend to offset the simple operation of supergene processes, such as, for example, the porosity of the country-rock, the relative porosity of the fractured or brecciated zone, the rate of oxidation, the changing relationship between the water-table and the surface, and recent variations in the position of the water-table that may have retarded or facilitated oxidation and enrichment. Unfortunately it was impossible to estimate with any accuracy the local effects of these minor factors, which to a considerable degree would tend to vitiate conclusions bearing on the principal thesis. In the hope, however, that microscopic study might supply some positive evidence in support of the theory that the present mixture of minerals is directly related to the physiographic history, specimens were collected, so far as possible, at various elevations in order that zonal changes might be detected. Microscopic examination of the specimens collected at the several elevations, although not negative, does not, however, substantiate the hypothesis of physiographic control. Interest, therefore, centers in the genesis of the ore and in the aggregate of minerals present.

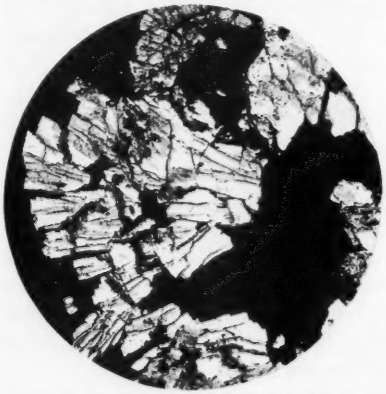

FIG. 5. A coarser phase of the prehnite replaced by bornite (black). The prehnite may be an endomorphic product resulting from a reaction between the andesite magma and fragments of intruded limestone. Such fragments in the crush-zone are partially replaced by primary sulphides.

Petrography.—The country-rock in which the deposit occurs is an augite andesite, simple in history and in composition. Samples taken outside of the mineralized zone exhibit no traces of mineralizing action and but slight evidence of deformation or of extensive alteration. The mineralized zone is brecciated, and a limestone is involved in the breccia. Field evidence shows that the andesite is intrusive into the limestone, and that fragments of the latter are included in the andesite breccia that forms the locus of the ore deposit.

The andesite is moderately porphyritic with a fine pilitic groundmass composed of little laths of plagioclase, altered glass, and minute specks of magnetite. The phenocrysts are plagioclase feldspars ranging from andesine to labradorite, twinned after the Carlsbad, albite and pericline laws; they are rarely zoned, but they exhibit slight resorption. They have been partly altered to sericite, carbonate, and chlorite, and carbonate occurs in minute fractures which cross the phenocrysts and extend into the groundmass as well, but which commonly die out within the limits of the thin section. Albite is associated with, and occupies the same veinlets as, the carbonate, cutting across the plagioclase phenocrysts and through the groundmass of the rock.

These alteration products were undoubtedly connected with the mineralizing processes responsible for the deposition of the ore; for they are entirely absent from specimens taken a short distance away from the mineralized zones, which display no petrographic evidence of deformation or alteration of any consequence.

In addition to the feldspar, idiomorphic crystals of augite and aggregates of augite crystals smaller than the feldspar phenocrysts are sparingly distributed and are always perfectly fresh. There are occasional crystals of olivine in various stages of modification. Some of them are entirely altered to carbonate, whereas others still contain remnants of unchanged olivine. The rock is thus an olivine-bearing augite andesite, on the borderline between the andesites and basalts.

The andesite itself was not the source of the copper, nor was it responsible for the mineralization, though it is possible that

the ore may have been genetically connected with the magma-source of the andesite. There is some evidence of endomorphism in the ore, but this is judged to have been the result of the action of the andesite magma on included fragments of limestone and not necessarily related in any way to the actual mineralization period itself.

As a result of the reaction between the andesite magma and xenoliths of the limestone into which the andesite was intruded, there were formed a little chlorite, a considerable amount of very yellow and strongly pleochroic epidote, a zeolite that responds to all of the optical tests for laumontite, and a peculiar radiate, colorless mineral that could not be identified in thin-section. By the use of fragments and immersion media, the indices and optical properties were determined with the following results:

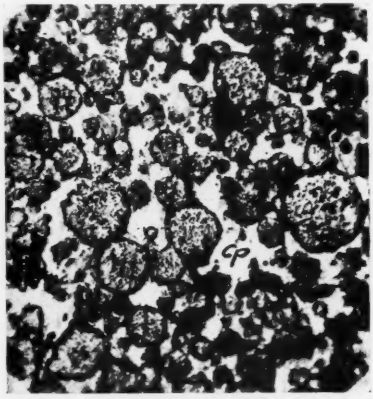

FIG. 6. Ore from upper tunnel. Polished surface. Round pyrite grains in a matrix of chalcopyrite (*Cp*). They resemble oölitic pyrite but may possibly be pyrite pseudomorphous after structures in the limestone that occurs in fragments mixed with andesite in the crush-zone. ×270.

$N\alpha = 1.623 \pm .003$; $N\beta = 1.633 \pm .003$; $N\gamma = 1.655 \pm .003$. $\gamma - \alpha = 0.032$. The mineral has parallel extinction and negative

elogation; it is optically positive with large 2 E. Some fragments exhibit very fine, microcline-like twinning lamellae which are somewhat faint, but usually easily discernible. These characters and constants correspond to those given for prehnite, although the structure is a little unusual for that mineral. (See Fig. 4:)

Sulphide Ore.—The initial primary sulphides are pyrite, chalcopyrite, and bornite. In the samples of ore studied not all three of these are uniformly present, but usually chalcopyrite and bornite occur together. Both quartz and carbonate are involved with the products of primary mineralization, so that during the actual ore-forming process quartz, carbonate, pyrite, chalcopyrite, and bornite were introduced into the andesite breccia, which apparently offered good channels of circulation for the mineralizing solutions. The ore is confined to the brecciated zone; it does not penetrate the wall to any extent, and where intersecting

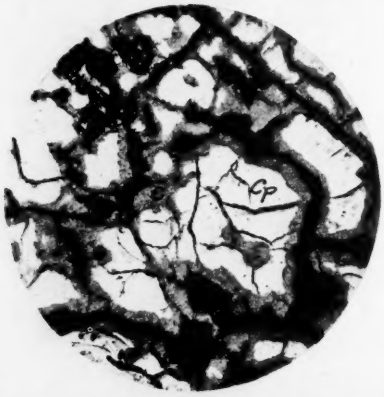

FIG 7. Polished plate of ore from main ravine. Chalcocite (*C*) encroaching upon and partially replacing chalcopyrite (*Cp*). Black areas are chiefly chrysocolla and malachite. This illustrates the formation of supergene chalcocite at the expense of the chalcopyrite, and the concomitant or very closely following alteration of the chalcocite to malachite and chrysocolla. ×50.

fissures occur more ore has been deposited than elsewhere, and the partially silicated fragments of limestone involved with the andesite breccia in the crush-zone have been slightly replaced by the primary sulphides. This feature is illustrated in Fig. 5, which shows replacement of the prehnite by bornite.

One of the samples of ore from the upper tunnel contains spherical grains of pyrite distributed through a matrix of chalcopyrite (Fig. 6). The pyrite grains are not uniform in size and they are quite unlike the rest of the pyrite that is associated with the ore, as that occurs in the usual crystal form. There is no evidence of attack on the spherical grains by the chalcopyrite in which they occur, and grains of this character were observed in but one specimen of the ore. The ore has replaced, at least in part, fragments of the limestone that occur as xenoliths in the andesite and that were so distributed as to be included in the crush-zones or fracture zones that form the locus of the deposit, so that there is a possibility that this rather unusual form of pyrite may represent small fossils in the limestone xenoliths, replaced by the pyrite, but there is no definite proof of this.

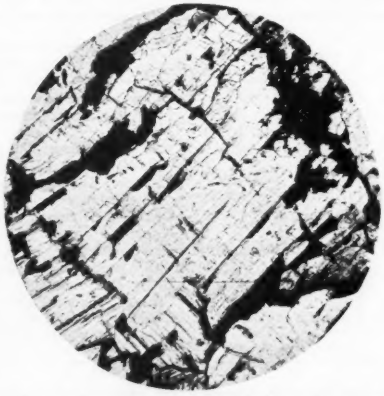

FIG. 8. Ore from upper tunnel. Polished surface. Supergene chalcocite retaining the structure of some primary mineral, possibly bornite, which it replaced. Black areas are patches of oxidation products. ×50.

Oxidation and Enrichment.—Oxidation and supergene enrichment have played a prominent part in the history of the ore subsequent to its deposition. Chalcocite, malachite, azurite, chrysocolla, limonitic products, and very small amounts of one or two rarer secondary minerals of much less certain identification (pisanite (?) and atacamite (?)) have developed as weathering progressed. The chalcocite cuts the primary chalcopyrite and bornite in veinlets and encroaches upon them along the margins of the grains, replacing them wholly or in part; in places the supergene chalcocite retains a structure that was probably inherited from replaced bornite. Fig. 7 shows partial replacement of chalcopyrite by chalcocite, and Fig. 8 shows inherited structure in the chalcocite.

Results of a petrographic analysis of the specimens collected at various elevations in the deeply cut ravine along which the ore outcrops are presented in Table I. As the table indicates, primary sulphides are mixed with secondary chalcocite and oxidation prod-

TABLE I.

PETROGRAPHIC ANALYSIS OF ORE SAMPLES ACCORDING TO ELEVATION.

Elevation in Feet.[8]	Sample No.	Primary Sulphides.	Supergene—Including Oxidation Products.
1,300	13	Destroyed	Chalcocite, chrysocolla, malachite, azurite, limonitic products.
1,300	12	Chalcopyrite, pyrite	*None.*
1,300	10–11	Bornite	Chalcocite, chrysocolla, malachite, limonitic products, pisanite (?).
1,300	9	Bornite	Chalcocite, malachite, chrysocolla, limonitic products.
1,250	8	Bornite	Chalcocite, limonitic products.
1,250	7	Pyrite	*None.*
1,100	5–6	Chalcopyrite, bornite	Chalcocite, chrysocolla, malachite, limonitic products, pisanite (?).
1,025	3	Chalcopyrite, bornite	Chalcocite, malachite, chrysocolla, azurite (?), limonitic products.
1,025	1	Bornite	Chalcocite, malachite, chrysocolla, azurite (?), limonitic products.

ucts at all elevations. A variety of factors may be called upon

[8] The elevations given are based on barometric readings and are only approximate.

to explain the association of hypogene and supergene minerals at the same elevation. Inasmuch as the assemblage persists without change in the entire 300 feet of the section exposed in the ravine, it is impossible to establish any connection between the cycles of peneplanation and diatrophic movements on the one hand, and the mineral association in the ore, on the other. The varying degree of porosity in different parts of the crush-zone has plainly been of more immediate importance in governing the operation of supergene processes than the more remote and less tangible factor of physiographic control.

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THE ORIGIN OF NICKEL SILICATES AT WEBSTER, NORTH CAROLINA.[1]

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INTRODUCTION.

NICKEL silicates have been found in many of the dunite areas of the Appalachian region, but they are probably more abundant at Webster, North Carolina, than at any other locality. The Webster dunite mass, which is the largest in the State, has not been highly serpentinized, and for this reason it shows the relations between primary and secondary minerals with unusual clearness. Thus favorable conditions are presented for studies of the genesis of nickel silicates, and four opportunities to visit the locality have allowed detailed studies of the area and the collection of numerous specimens as progressive erosion has exposed new material and new relations. These studies indicated that the nickel silicates had been formed by an unusually interesting geologic process and suggested that the problem deserved further study.

LOCATION.

The Webster dunite area is located at the town of Webster, in Jackson County, western North Carolina, near the central part of the Cowee quadrangle. Dillsboro, on the Murphy branch of the Southern Railway, is about 3½ miles northwest, and Sylvia only a little farther to the northeast. Tuckasegee River, the major stream of the region, cuts across the dunite mass just south of Webster. The region is in the mountainous part of the State, and the altitude is about 2,150 feet, but the maximum relief within the dunite area is only a few hundred feet. The Webster

[1] Published by permission of the Director of the U. S. Geological Survey and the Secretary of the Smithsonian Institution.

[2] Of the U. S. Geological Survey.

[3] Of the U. S. National Museum.

dunite body has the form of an elliptical ring with a major axis about 6 miles long that trends northeast and a minor axis about 3½ miles long. The continuity of the mass is broken only in a few places along the east limb of the ellipse. Along the west limb the width narrows to 10 feet of talcose schist in places. The broadest part of the ring is near the southwest loop, at Webster, where the width is about 1,600 feet.

PREVIOUS WORK.

The peridotite areas of North Carolina have been described by Pratt and Lewis,[4] and their paper should be consulted by those interested in the detailed petrographic descriptions of the Webster dunite body. Barlow[5] has discussed the secondary origin of the nickel silicates and given a history of the attempts at nickel mining in the region.

The presence of nickel silicates at Webster led to the erection of a plant to recover the nickel by electrolytic smelting. The nickel-bearing veins are comparatively small, the nickel content is not high, and the successful reduction of the ores presented a difficult problem, so the attempt to mine and smelt nickel was soon abandoned.

PETROLOGY OF THE DUNITE AND ASSOCIATED ROCKS.

Dunite is the dominant rock type in the Webster intrusive mass, but a band of pyroxene rock called websterite occurs near the east border of the broad southwest loop of the ringlike dunite body. The websterite mass has a width of about 550 feet and a length of about a mile, and Tuckasegee River cuts across it.

Parts of the dunite mass are made up of practically pure olivine grains with only a minute inclosing film of serpentine and scattered grains of chromite, bronzite, actinolite, and talc. The freshest dunite observed occurs where chromite has been mined south of Tuckasegee River and near the east border of the dunite

[4] Pratt, Joseph Hyde, and Lewis, J. Volney, "Corundum and the Peridotites of Western North Carolina," North Carolina Geol. Survey, vol. 1, 1905.

[5] Barlow, Alfred E., "On the Nickel Deposits of Webster, Western North Carolina, *Canadian Min. Inst. Jour.*, vol. 9, pp. 303–316, 1906.

mass, about three-quarters of a mile southeast of Webster. The fresh rock is a very light yellow-green. The olivine grains are anhedrons 0.1 to 2.0 millimeters in diameter, and almost no serpentine is seen under the microscope. Bronzite is present but rare. Chromite in the form of isolated grains or of continuous bands 1 to 20 millimeters wide is always associated with kammererite and less commonly with talc, ankerite, and actinolite. A small amount of nickel silicates is associated with talc veinlets and in joint planes, but no large veins were observed at this locality.

There has been some prospecting for nickel half a mile south of Webster, on the south side of Tuckasegee River, where the electrolytic plant for its extraction was erected. A broad crosscut has exposed weathered dunite and nickel-bearing veins for a maximum depth of 20 feet, and for a distance of several hundred feet. Part of the dunite is similar to that just described, but chromite is present only as disseminated grains, the fresh olivine has a light yellow-green color, but other parts that are in sharp contact with fresh dunite have been partly serpentinized and have a dark olive-green color. The partly serpentinized material contains about 40 per cent. of fresh olivine and about 60 per cent. of serpentine, which has formed on all the crystal boundaries and along many of the fractures within crystals.

The locality a quarter of a mile east of Webster where nickel silicates are developed has the same type of dark olive-green, partly serpentinized dunite that occurs at the "nickel mine." Alternating bands 1 to 10 centimeters wide show a distinct difference in texture, and this difference is accentuated by weathering, so that the material superficially resembles a bedded deposit. Pratt and Lewis have shown that the lamination is due to parallel shearing that was localized along parallel zones in the dunite.[6]

Websterite, which was first described by Williams,[7] is a rock that is composed of a bright-green monoclinic pyroxene, reddish-brown bronzite, and variable amounts of pleonast.

Minerals of Hydrothermal Origin.—The original minerals of

[6] Pratt, Joseph Hyde, and Lewis, J. Volney, *op. cit.*, p. 93.

[7] Williams, G. H., *Am. Geologist*, vol. 6, p. 44, 1890.

the dunite and the other rocks of the intrusive mass are olivine of the dunite; chromite that has usually been considered primary; bronzite, the orthorhombic pyroxene; and the monoclinic pyroxene of websterite. These constitute a very simple mineral facies, but the secondary minerals that have been formed by hydrothermal processes are more numerous and complex in their relations. These fall into two groups—minerals that are sparsely disseminated in the dunite itself and minerals that occur in well-defined veins.

Actinolite, kammererite, diallage, and talc that are disseminated in dunite are deuteric minerals formed after the intrusion of the dunite, by residual solutions that were possibly concentrated during the crystallization of olivine, but these solutions evidently were not sufficiently abundant to produce extensive alterations in the dunite. Serpentinization is no doubt a slightly later hydrothermal process, but it was probably produced by greater concentration of solutions from sources that were possibly deeper in the cooling mass. Serpentinization is distinctly localized with nearly sharp contacts between serpentine and fresh dunite, and this indicates that some parts of the dunite were more actively attacked by the incoming solutions than others.

VEINS IN THE DUNITE.

At the "nickel mine" and by the roadside a quarter of a mile east of Webster the dunite is cut by numerous veins that now contain the nickel silicates discussed in this paper. These veins were probably formed at about the same time as the disseminated hydrothermal minerals of the dunite. They reach a maximum width of 30 centimeters and contain the minerals anthophyllite, tremolite, talc, green chlorite, vermiculite, and rarely kammererite and albite. Pure talc forms small veinlets of another type that are very abundant at the locality three-quarters of a mile southeast of Webster. Ankerite is associated with chromite, kammererite, and actinolite in small veins in the dunite.

There is a definite relation between the size of the veins and their mineral composition. The smallest ones, 3 to 4 centimeters

in width, are composed of anthophyllite and talc or of anthophyllite, tremolite, and talc. Those that are somewhat larger have an inner core of vermiculite, and commonly there is a transition zone in which anthophyllite, tremolite, and vermiculite or green chlorite are intergrown. The largest veins, 25 or 30 centimeters wide, have a central zone that contains irregular, discontinuous masses of coarse-grained albite.

It is evident that the veins have been somewhat altered since they were first formed, but the original minerals are easily determinable. Talc is an alteration product of anthophyllite and tremolite, and chlorite and vermiculite are derived from biotite. No biotite was observed at Webster, but veins of the same type at Corundum Hill, Macon County, N. C., contain biotite that has not been completely altered to vermiculite. The coarse-grained albite has been partly altered to serpentine along cleavage cracks and twinning planes as shown in Figs. 1 and 2. It is evident, therefore, that the original minerals of the veins were anthophyllite, tremolite, biotite, and rarely albite. Kammererite is a rare associate of these minerals, but its mode of origin is not clear.

The minerals in the veins are of a type that is generally recognized as being of hydrothermal origin, and Larsen in an unpublished paper[8] has made a detailed study of such veins in dunite and serpentine, and shows that they must have been formed by hydrothermal processes. Early solutions formed the veins, and at a later stage the nature of the vein-forming solutions must have changed, for part of the earlier products of crystallization were unstable in the new environment, and talc, chlorite, vermiculite, and serpentine were formed at the expense of older minerals. It seems probable that the serpentinization of the dunite and the formation of veins of deweylite (a variety of serpentine) constituted the final episode in the escape of hydrothermal solutions and their reaction with older minerals.

The minerals of the dunite and the veins in the dunite may be grouped as follows:

[8] Larsen, Esper S., ECON. GEOL., vol. 23, pp. 398, 433, 1928.

TABLE 1. MINERALS IN THE WEBSTER DUNITE AREA.

Pyrogenic minerals:
- Olivine.
- Bronzite.
- Green pyroxene.
- Picotite.
- Chromite

Early hydrothermal minerals:
- Anthophyllite.
- Actinolite.
- Tremolite.
- Biotite.
- Albite.
- Diallage.
- Chrome mica?

Late hydrothermal minerals:
- Talc.
- Kammererite.
- Green chlorite.
- Vermiculite.
- Ankerite.
- Serpentine.
- Deweylite.

TABLE 2. PARAGENESIS OF MINERALS IN WEBSTER DUNITE AREA.

Minerals in veins.		Minerals in dunite.	
Hydrothermal minerals.	Secondary minerals formed by hydrothermal alteration.	Secondary minerals formed by hydrothermal alteration.	Pyrogenic minerals.
Anthophyllite →	Talc	Talc, Serpentine ←	Olivine
Tremolite →	Talc		
Biotite →	Green chlorite, Vermiculite	Talc ← Diallage ←	Bronzite, Green pyroxene, Chromite, Picotite
Albite →	Serpentine		
Unknown mineral →	Kammererite		Hydrothermal minerals
		Kammererite ←	Unknown mineral, Actinolite, Ankerite

NICKEL SILICATES.

The nickel minerals at Webster assume several forms. A bright-green material with the properties of genthite forms thin films on joint cracks but is a subordinate nickel mineral. The films are commonly not over 1 or 2 millimeters thick and are usually associated with chalcedony, as shown in Fig. 5. The thicker veins of the type consist dominantly of chalcedony with enough nickel silicate to give it a green color.

A second type of serpentine-like mineral forms dark-green veins that are as a rule not more than 10 millimeters in width. This material has a resinous appearance, is semitransparent, and has a conchoidal fracture. In thin section it is nearly isotropic, and evidently it is a nickeliferous deweylite. A metacolloidal type of nickeliferous deweylite is shown in Fig. 4. The same mineral also forms coatings around vermiculite masses, where it has a bright apple-green color, botryoidal surface, and numerous shrinkage cracks. The albite previously mentioned is cut by irregular veinlets of serpentine, as shown in Fig. 2, and serpentine has formed small rhombic areas in alternate albite twinning lamellae, as shown in Fig. 1. Part of the serpentine is nickeliferous and gives the feldspar a bright-green color, but the nickel-free serpentine secondary to albite is white.

The most abundant nickel minerals in the Webster area occur in the hydrothermal veins. The vermiculite of these veins is bright green and nickel-bearing where the veins extend into the red residual soil but is not nickel-bearing in fresh dunite. A few feet below the base of the red residual soil the vermiculite becomes darker green, and where the veins penetrate fresh dunite it has the usual dark bronzy-brown color and is low in nickel. The coarse-grained micaceous habit of the nickeliferous vermiculite is shown in Fig. 3. The fine-grained micaceous aggregates of nickel silicate are highly plastic when wet. It is interesting to note that a material that is made up exclusively of crystal plates averaging nearly 1 millimeter in maximum diameter shows greater plasticity than many clays. Microscopic and chemical studies show that two minerals are represented by this micaceous ag-

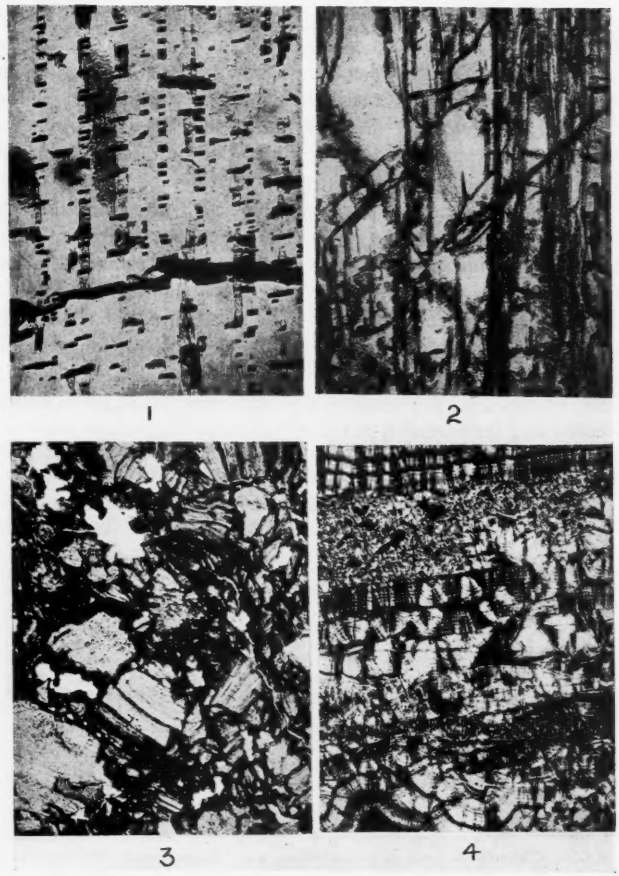


FIG. 1. Photomicrograph of albite from the center of a large hydrothermal vein. Alternate albite twinning lamellae are partly altered to serpentine. × 20.

FIG. 2. Same as Fig. 1, with irregular veinlets of serpentine. × 20.

FIG. 3. Photomicrograph of nickeliferous vermiculite showing the micaceous habit. × 20.

FIG. 4. Photomicrograph of nickeliferous deweylite with metacolloidal structure similar to that in some chalcedony. × 20.

gregate. One is nickel-bearing vermiculite that usually forms large, distinct, micaceous plates. The other occurs in smaller crystal plates that form a matrix around vermiculite crystals in some specimens; more rarely it occurs in pure masses. The chemical analyses show that this fine-grained micaceous mineral is a serpentine but is evidently an alteration product of vermiculite, from which it has inherited its structure.

Thus at Webster there are nickel minerals with several distinct habits, but they can all be referred to two mineral groups. The large, distinct mica-like plates are nickeliferous vermiculite. The fine-grained bright-green plastic material is a micaceous serpentine; the nickeliferous deweylite is a serpentine that is high in water and commonly isotropic; and the genthite on joint cracks is a variety of serpentine.

The following analyses show the nickel minerals of the Webster locality and the variation in nickel content.

TABLE 3.

ANALYSES OF NICKELIFEROUS VERMICULITES FROM WEBSTER, N. C.

	1	2	3	4	5	6[a]	7[a]
SiO_2	34.92	35.28	37.18	36.54	33.30	35.70	34.76
TiO_2	.60	.60	.66	.....	1.02	.....	.....
Al_2O_3	13.06	13.02	9.56	16.96	14.72	12.00	14.86
Fe_2O_3	2.74	3.80	3.20	2.78	5.02	3.40	2.74
FeO	.54	.54	.68	.95	1.36	.....	.41
NiO	3.24	3.26	6.70	2.32	2.14	5.34	11.25
MgO	23.92	23.86	22.84	19.78	22.00	25.90	18.18
CaO	.24	.16	.56	.06	.12	.32	.40
H_2O at 110° C.	9.00	8.60	7.12	9.24	8.56	12.00	12.60
H_2O at 400° C.	5.00	3.26	3.26	3.80	4.94	.....	.....
H_2O at red heat	6.30	7.38	7.22	7.36	5.86	.....	.....
H_2O at + 120° C.	.....	.....	.....	.....	.....	7.00	5.20
	99.56	99.76	98.98	99.79	99.04	101.66	100.40

[a] Ross, Clarence S., and Shannon, Earl V., "Nickeliferous Deweylite and Serpentine from Webster, N. C.," *Am. Mineralogist*, vol. 11, pp. 90–93, 1926.

Analyses 1, 2, 3, 4, and 5 by Forest A. Gonyer; analyses 6 and 7 by Earl V. Shannon.

1. Bronzy greenish-yellow plates with a maximum diameter of 2 centimeters.

2. Bronzy greenish-yellow flakes averaging 2 millimeters in diameter.

3. Fine bronzy greenish-yellow flakes averaging 0.5 millimeters in diameter. Nos. 1, 2 and 3 were all from the same specimen. The analysis shows that the larger plates had approximately the same nickel content but the finest portion, No. 3, contained about twice as much nickel, and the low alumina content indicates that the vermiculite was partly altered to a serpentine-like mineral.

4. Light greenish-yellow plates of vermiculite of great purity.

5. Dark-gray to purplish-gray plates of vermiculite about 2.5 centimeter in diameter with a metallic luster, due to thin films of magnetite between the plates. The specimen was collected near the bottom of an open cut, where the dunite was only partly weathered and represents the least modified vermiculite of the series.

6. Bright apple-green plates of vermiculite about 8 millimeters in diameter.

7. A fine-grained aggregate in which the smaller plates were partly altered to a serpentine-like mineral.

Samples 1, 2, 6 and 7 were clear, pure vermiculites. In each of these the ratio of $SiO_2 : Al_2O_3 + Fe_2O_3 : MgO + NiO + FeO : H_2O$—that is, $SiO_2 : R_2O_3 : RO : H_2O$—is very close to 4 : 1 : 4 : 6. The ratio of Nos. 4 and 5 is 3 : 1 : 3 : 6. This seems to indicate that two types of vermiculite were represented in these analyses, and their formulas are $4MgO.Al_2O_3.4SiO_2.6$ to $7H_2O$ and $3MgO.Al_2O_3.3SiO_2.6$ to $7H_2O$, where varying proportions of NiO and FeO proxy Mgo and a little Fe_2O_3 proxies Al_2O_3.

TABLE 4.

ANALYSES OF NICKELIFEROUS MINERALS OF THE SERPENTINE GROUP FROM WEBSTER, N. C.

	1	2	3[a]	4[b]
SiO_2	41.00	38.86	39.36	43.26
Al_2O_3	.22	5.00	2.76	1.20
Fe_2O_3	3.28	1.50	2.77	
FeO	.40	.68	....	....
NiO	15.56	12.08	2.57	4.20
MgO	22.86	24.80	36.71	30.00
CaO	.30	.64	1.32	.24
H_2O at 110° C.	6.22	4.92	1.54 at 120°	+10.54
H_2O at 400° C.	2.50	2.74	13.85 above 120°	− 9.30
H_2O at red heat	7.24	8.52	....	....
	99.58	99.74	100.88	98.74

[a] Originally described by Ross, Clarence S., and Shannon, Earl V., "Nickeliferous Vermiculite and Serpentine from Webster, N. C.," *Am. Mineralogist*, vol 4, pp. 90–93, 1926.

[b] Ross, Clarence S., and Shannon, Earl V., "So-called Genthite from Webster, N. C.," *Am. Mineralogist*, vol. 10, pp. 444–445, 1925.

Analyses 1 and 2 by Forest A. Gonyer; analyses 3 and 4 by Earl V. Shannon.

Analysis 1 represents a fine-grained aggregate of micaceous scales 1 millimeter or less in diameter that have an apple-green color and are plastic when wet. The material resembles fine-grained vermiculite, but the indices of refraction and the chemical composition show that it is a serpentine. No. 2 is made up of fine plates separated from coarse vermiculite. It evidently contains some vermiculite, and so the analysis does not represent a pure serpentine mineral. No. 3 is light-green opal-like material with conchoidal fracture and numerous shrinkage cracks. No. 4 is a nickeliferous deweylite of apple-green color, waxy luster, and conchoidal fracture. Under the microscope it shows the chalcedony-like metacolloidal structure shown in Fig. 4.

DUNITE WEATHERING.

Olivine is very unstable in the zone of oxidation and weathers to a porous, friable soil, and so in general the relief is moderate in the Webster area and the mantle of weathered material is not usually thick. The surface soil is dark reddish brown and supports a meager vegetation. Below this is friable dark-red residual material that is commonly not more than 8 to 12 feet thick with the chemical composition shown in 1, Table 12. This grades downward into a light-yellow porous material with the chemical composition shown in 3, Table 12 that retains much of the structure of dunite, and this in turn gradually merges into fresh dunite, or partly serpentinized dunite. The upper surface of fairly fresh dunite is irregular, and rounded masses locally project far into the weathered material. The rapidity of weathering seems to be controlled largely by the ease with which water can penetrate the mass, and the more porous parts of the dunite weather fastest.

GENESIS OF NICKEL SILICATES.

It has long been recognized that the nickel ores of New Caledonia were formed through the weathering of a nickel-bearing peridotite that was originally composed of olivine and enstatite but is now largely serpentine. Barlow [9] has described the same process at Webster and shown that the dunite is the source of the

[9] Barlow, Alfred E., Canada Geol. Survey Ann. Rept., vol. 14, pt. H, p. 183, 1904.

nickel. The analyses of olivine in Table 6 and of serpentine in Table 11 show that the original minerals contained 0.22 to 0.44 per cent. of nickel and confirm the long-accepted belief that the dunite is the original source of the nickel.

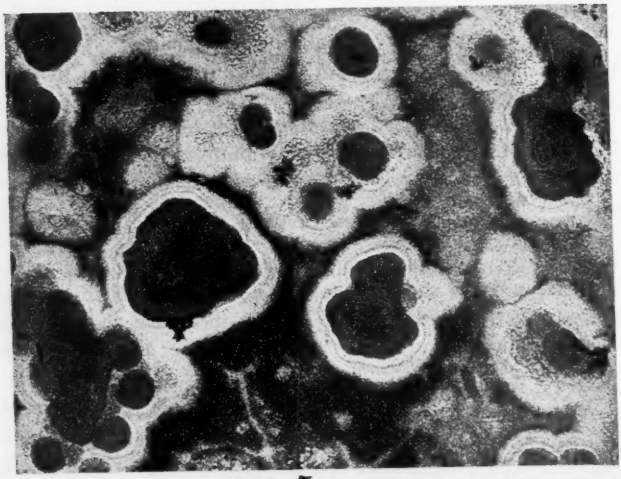
Some of the nickel silicates that form films or joint cracks in the dunite are clearly supergene minerals, but most of the nickel silicates are now found in the vermiculite-bearing veins of hypogene origin. Veins of the same type are found in many of the dunite and serpentine areas of the eastern United States. Pratt and Lewis[10] and Gordon[11] have all described such veins, and Larsen[12] has shown that they must have been formed by hydrothermal processes. It is evident, then, that the veins at Webster which contain anthophyllite, tremolite, talc, vermiculite and more rarely albite, are hypogene in origin and entirely unrelated to supergene or weathering processes. The vermiculite of such veins is commonly free from nickel, and even at Webster the veins are not nickel-bearing where they cut fresh dunite. It is generally believed that the dunite is the original source of the nickel and that it has been concentrated during the course of weathering. The veins were originally composed of minerals that did not contain nickel, although they are now the dominant source of it; and for these reasons there must have been a transfer of nickel from dunite to vermiculite.

Vermiculite is essentially a hydrous aluminum silicate with magnesium and ferrous iron as loosely held bases, and it has an unusually perfect micaceous cleavage, which gives it a very large potential surface area. Minerals with this physical habit and chemical composition commonly exhibit the property of base exchange, like the zeolites and clay minerals. This fact suggests that nickel as it was set free from the weathering dunite has been fixed in the vermiculite-bearing veins by the chemical process called base exchange.

[10] Pratt, Joseph Hyde, and Lewis, J. Volney, "Corundum and the Peridotites of Western North Carolina," North Carolina Geol. Survey, vol. 1, 1905.

[11] Gordon, Samuel G., "Desilicated Granitic Pegmatites," *Acad. Nat. Sci. Philadelphia, Proc.*, vol. 73, pt. 1, pp. 169–192, 1921.

[12] Larsen, Esper S., *loc. cit.*



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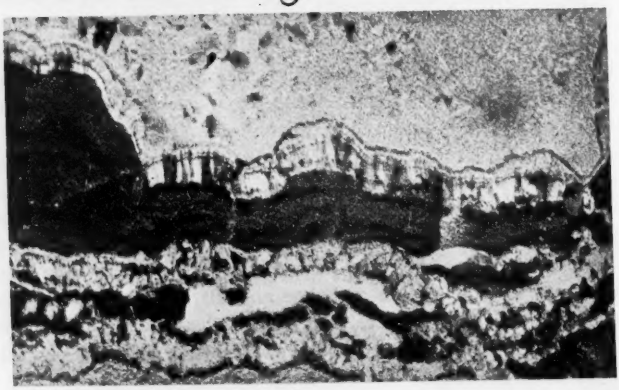

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FIGS. 5 AND 6. Photomicrographs showing alternate layers of chalcedony and genthite. Dark genthite and light chalcedony. 5 is cut nearly parallel to the layers and 6 perpendicular to the layers. × 23.

Base exchange is the chemical replacement of one base by another.[13] A well-known example which has been described by Lemberg[14] is the change of leucite into analcite by the action of hot solutions of sodium chloride, which brings about the replacement of potassium by sodium; at the same time water is added.

The simplest case of base exchange occurs where chemically analogous molecules are involved—that is, those that can proxy one another in all proportions, as MgO, FeO, and MnO do in many silicate minerals. The substitution of NiO for MgO is a reaction of this type, for nickel and magnesium have many analogous chemical properties.

The mass law and relative solubility are factors in promoting base exchange. The mass law tends to favor the reactions that involve the molecule that is in the greatest concentration, and differences in solubility tend to favor the fixation of the molecule that has the lowest relative solubility. Wells[15] has shown that nickel hydroxide, carbonate, and silicates are less soluble than the corresponding magnesium salts, and it seems evident that the relative solubility rather than the mass law controlled the formation of nickel silicates at Webster. The weathering of olivine involved the bringing into solution of relatively large proportions of magnesium and very small proportions of nickel. Mass action would tend to favor reactions involving magnesium, but such reactions have not occurred, and the less abundant but more insoluble nickel has been the base that has become fixed.

If base exchange has been the method of nickel transfer, chemical analyses should show a gradation from pure or nearly pure magnesium-iron vermiculites to those relatively high in nickel. The analyses given in Tables 3 and 4 show that there is such a gradation.

The geologic and chemical evidence that there has been a transfer of nickel and its substitution for magnesium in vermiculite,

[13] Sullivan, Eugene C., "The Interaction between Minerals and Water Solutions," U. S. Geol. Survey Bull. 312, pp. 10–36, 1907.

[14] Lemberg, J., *Zeitschr. f. Deutsch. geol. Gesell.*, vol. 28, p. 537, 1876.

[15] Wells, Roger C., "The Fractional Precipitation of Some Ore-forming Compounds at Moderate Temperatures," U. S. Geol. Survey Bull. 609, p. 45, 1915.

suggested that the process could be repeated in the laboratory. Several samples of vermiculite were prepared and sealed in a glass tube with the reagents $Ni(Cl)_2$, $Ni(Cl)_2 + NaCl$, and $Ni(NO_3)_2$. The sealed tubes were maintained at a temperature of 110° C. for one to two months. In all the experiments it was evident from the green color assumed by the vermiculite that it was becoming richer in nickel. The vermiculite treated with nickel chloride and sodium chloride seemed to take up nickel fastest. This material and the original vermiculite were analyzed. The results are shown in Table 5.

TABLE 5.

ANALYSES OF VERMICULITE FROM WIANT'S QUARRY, NEAR PILOT, MD., BEFORE AND AFTER TREATMENT BY NICKEL AND SODIUM CHLORIDE.

	Before.	After.
SiO_2	35.92	32.92
Al_2O_3	10.68	14.50
Fe_2O_3	10.94	10.04
FeO	.82	1.63
NiO	None	12.72
MgO	22.00	12.52
CaO	.44	.32
H_2O at 110° C.	10.50	4.42
H_2O at 400° C.	4.34	2.78
H_2O at red heat	5.00	8.26
	100.64	100.11

The vermiculite has taken up a surprisingly large amount of nickel (12.72 per cent.) during the comparatively short time of the chemical treatment. The ratios of the different groups of elements including MgO + NiO are practically the same in the two samples, and this shows that there has been no alteration of the treated samples and that the only effect has been the substitution of NiO for MgO.

The partly weathered dunite is very porous, and water penetrates it as easily as it would a sand bed. The analysis given in 1, Table 12 shows that the thoroughly weathered material is com-

posed dominantly of hydrous iron oxide and that MgO has been reduced to a minor constituent. It seems evident that freely circulating meteoric waters charged with carbon dioxide must have been the agent that dissolved and removed magnesium in the form of bicarbonate. Under the same conditions part of the nickel would go into solution as bicarbonate, but because of its greater insolubility it would tend to become fixed through the replacement of magnesium where the solutions came into contact with the magnesium-bearing vermiculite. Some of the iron of the original dunite may also have been removed by meteoric waters, but the porosity allowed a ready access of oxygen, and most of the iron was probably quickly oxidized and insoluble limonite formed.

The photomicrographs reproduced in Figs. 1 and 2, show a partial alteration of albite to serpentine, and this represents a profound change that was undoubtedly the result of hydrothermal reactions in a late stage of vein formation. Part of this serpentine is pure white and evidently nickel-free, but a part has taken up nickel in the same way as the vermiculite and gives the entire albite mass a vivid light-green color.

During the weathering of the dunite a nickel silicate formed relatively thin films on joint cracks, where it is usually associated with chalcedony. The deposition along joint cracks shows that it is entirely the result of weathering. It is of a somewhat paler green but has the same relations and habit as the genthite of Riddles, Oregon.

The paragenesis of the micaceous serpentine associated with vermiculite is not quite clear. The nickel-bearing part of the veins originally contained vermiculite, but now a micaceous serpentine forms a matrix around masses of vermiculite, and locally it forms pure masses. Many of the larger crystals with perfect micaceous cleavage have cores of yellowish-green vermiculite and irregular borders of bright-green micaceous serpentine. It is possible that this alteration of the vermiculite to serpentine began at the time the dunite became serpentinized and

is therefore a hydrothermal process. However, the most completely altered micaceous crystals have shrinkage cracks, between plates, so that the present volume of the crystal is commonly only one-half of the original volume. The open spaces could not have persisted if formed by hydrothermal solutions under deep-seated conditions, and so they are probably the result of surface weathering. Thus it seems evident that part and possibly all of the alteration of vermiculite to a micaceous serpentine-like mineral was the result of surface weathering.

Talc is the only other mineral that seems to have been enriched in nickel (see Table 10), and it is probable that this alteration also was the result of base exchange. The magnesium of talc appears to be a much less easily replacable base than the magnesium in vermiculite, and most of the talc does not contain large proportions of nickel.

The other minerals of the veins are anthophyllite, tremolite, and chlorite. These are very stable minerals, and analysis 3, Table 9, shows that there was no tendency for anthophyllite to acquire nickel through base exchange.

DISTRIBUTION OF NICKEL PRIOR TO WEATHERING.

As the nickel now found in the nickel silicates was derived from the dunite by the process of weathering, it is interesting to determine how the nickel was distributed in the original minerals.

The dominant original rock of the Webster intrusive mass is dunite composed almost exclusively of olivine but carrying a little chromite. Inclosed in the dunite is an elongated mass of websterite composed essentially of bronzite and green diopside. After the formation of the dunite it was permeated and partly altered by hydrothermal solutions, which formed small amounts of actinolite, talc, and kammererite. About the same time the hydrothermal solutions formed veins composed of anthophyllite, tremolite, biotite (now vermiculite or chlorite), and albite. At a later stage the olivine was partly altered to serpentine. The following

analyses show the chemical composition of these minerals and the distribution of the nickel:

TABLE 6.

ANALYSES OF OLIVINE FROM NORTH CAROLINA.

	1	2	3	4	5	6
SiO_2	39.14	38.36	38.28	40.14	41.89	41.17
Al_2O_3	.52	.58	2.96	.06	Trace	.....
Fe_2O_3	2.38	1.58	.....	1.12	.....	.....
Cr_2O_3	.....	.....	.....	.....	.58	.....
FeO	6.04	6.62	7.88	5.18	7.39	7.35
MgO	51.64	51.50	50.28	53.38	49.13	49.16
NiO	.34	.34	.36	.44	.35	.41
CO	.....	.....	.....	.....	Trace	.....
CaO	.08	.10	.36	.12	.06	.04
MnO	.....	.09	.64	.09	Trace	.....
Loss on ignition	.....	.....	.....	.....	.82	.69
Insoluble	.....	.....	.....	.....	.....	1.23
	100.14	99.17	100.76	100.53	100.22	100.05

1. Olivine from dunite partly altered to serpentine, nickel mine half a mile south of Webster. The serpentine given in No. 1, Table 11, is from the same specimen. Forest A. Gonyer, analyst.

2. Olivine from an unusually fresh dunite mass that is exposed in a railroad cut 2 miles west of Balsam Gap. Forest A. Gonyer, analyst.

3. Olivine from a fresh dunite at chrome mine three quarters of a mile southwest of Webster. Forest A. Gonyer, analyst.

4. Olivine from fresh dunite at chrome mine three quarters of a mile southwest of Webster. The chromite given in Table 8, Nos. 4 and 5, is from the same specimen. Forest A. Gonyer, analyst.

5. Olivine from Webster. Frederick A. Genth, analyst; *Am. Jour. Sci.*, vol. 33, p. 199, 1862.

6. Olivine from Webster. T. M. Chatard, analyst; *Am. Jour. Sci.*, vol. 33, p. 202, 1861.

TABLE 7.

ANALYSES OF ROCKS FROM NORTH CAROLINA.

	1	2	3	4
SiO_2	41.89	40.74	55.14	41.58
Al_2O_3	Trace	Trace	.66	.14
Fe_2O_3	.....	.....	3.48	.....
Cr_2O_3	.....	.....	.25	.....
FeO	7.39	7.26	4.73	7.49
MgO	49.13	49.18	26.66	49.28
NiO	.35	.39	.11	[a] .34
CaO	.06	.02	8.39	.11
MnO	.....	.....	.03	.....
Na_2O	.....	.....	.30	.....
P_2O_5	.....	.....	.23	.....
H_2O	.82	.76	.38	1.72
Chromite	.58	1.83	.....	.....
TiO_2	.....	.....	Trace	.....
	100.22	100.18	100.36	100.66

[a] Includes traces of CO and Mn.

1 and 2. Dunite from Webster. Frederick A. Genth, analyst; U. S. Geol. Survey Bull. 74, p. 47, 1891.

3. Websterite from Webster. E. A. Schneider, analyst; Williams, G. H., *Am. Geologist*, vol. 6, pp. 35–49, 1890.

4. Dunite from Corundum Hill. T. M. Chatard, analyst; U. S. Geol. Survey Bull. 42, p. 55, 1887.

TABLE 8.

ANALYSES OF ACCESSORY MINERALS OF DUNITE FROM WEBSTER, N. C.

	1	2	3	4	5
SiO_2	53.69	53.62	52.34	.36	.36
Al_2O_3	2.88	.97	2.04	10.08	10.08
Fe_2O_3	.34	.....	.96	....	6.63
Cr_2O_3	.36	.50	.46	55.39	55.39
FeO	8.42	9.06	2.88	22.72	16.76
MgO	31.94	33.53	17.56	10.72	10.72
NiO	.....	.....	.....	Very small trace	Very small trace
CaO	2.11	1.75	23.96	.36	.36
MnO	.22	.....	.09	Trace	Trace
H_2O	.....	.19	.....	....	.....
	[a] 99.96	99.62	100.29	99.63	100.30

[a] Low summation probably indicates the presence of a small content of alkalies.

1. Bronzite from websterite. Forest A. Gonyer, analyst.

2. Bronzite. Baskerville, analyst; Pratt, Joseph Hyde, and Lewis, J. Volney, North Carolina Geol. Survey, vol. 1, p. 288, 1906.

3. Green pyroxene (diopside) websterite. Forest A. Gonyer, analyst.

4. Chromite, chrome mine three-quarters of a mile southeast of Webster. Associated with the olivine given in 4, Table 6. Forest A. Gonyer, analyst.

5. Same as No. 4 recalculated to show state of oxidation of iron.

TABLE 9.

ANALYSES OF SECONDARY MINERALS OF DUNITE AND VEINS FROM NORTH CAROLINA.

	1	2	3	4	5
SiO_2	54.36	30.78	54.48	45.14	.....
Al_2O_3	2.90	12.82	4.68	17.59	66.63
Fe_2O_3	.82	1.56	.....	.....	1.80
Cr_2O_3	.....	3.54	.....	.79	Trace
FeO	2.02	2.91	8.16	3.45	11.35
MgO	24.74	35.54	29.80	16.69	19.86
NiO	.20	.22	.....	.21	.25
CaO	12.32	.14	.32	12.51	.11
MnO	.04	.....	.32	.....	.....
Na_2O	.....	.....	.....	2.25	.....
K_2O	.....	.....	.....	.36	.....
H_2O at − 110° C.	.....	.18	None	1.34	.....
H_2O at + 110° C.	1.82	12.48	1.22		.....
	99.22	100.17	[a] 98.98	100.33	100.00

[a] Low summation probably indicates a small content of alkalies.

1. Actinolite from chrome mine three-quarters of a mile southeast of Webster. Forms small green crystals that have partly replaced the olivine represented in No. 2, Table 6. Forest A. Gonyer, analyst.

2. Kammererite from chrome mine three-quarters of a mile southeast of Webster. Associated with olivine represented in No. 3, Table 6, and chromite represented in Nos. 3 and 4, Table 8. Forest A. Gonyer, analyst.

3. Anthophyllite from nickel mine, half a mile south of Webster. Forest A. Gonyer, analyst.

4. Amphibole (edenite) from Buck Creek, Clay County. Frederick A. Genth, analyst; U. S. Geol. Survey Bull. 74, p. 45, 1891.

5. Spinel from Corundum Hill. Frederick A. Genth, analyst; *Am. Philos. Soc. Proc.*, vol. 13, p. 368, 1873.

TABLE 10.

ANALYSES OF TALC FROM WEBSTER, N. C.

	1	2	3
SiO_2	57.68	64.44	53.91
Al_2O_3	1.96	.48	2.65
Fe_2O_3	2.12	.....	.....
FeO	1.92	1.39	1.46
MgO	32.60	33.19	19.39
NiO	.32	.23	15.91
CaO	.44	.....	.....
H_2O at − 110° C.	.....	.....	6.30
H_2O at + 110° C.	2.08	.34	
	99.12	100.07	99.62

1. Talc from chrome mine three-quarters of a mile southeast of Webster. Forest A. Gonyer, analyst.

2. Talc. Frederick A. Genth, analyst; U. S. Geol. Survey Bull. 74, p. 61, 1891.

3. Talc. Backman, analyst; *Am. Chem. Jour.*, vol. 8, p. 48, 1886.

TABLE 11.

ANALYSES OF SERPENTINE FROM NORTH CAROLINA.

	1	2	3	4
SiO_2	35.56	41.90	43.87	42.94
Al_2O_3	2.46	.71	.31	1.72
Fe_2O_3	4.62	.91	.....	3.33
FeO	2.02	Undt.	7.17	1.88
MgO	39.88	40.16	38.62	36.53
NiO	.22	.10	.27	.61
CaO	.10	.....	.02	.....
MnO	.....	.....	Trace	.....
H_2O at − 110° C.	.88	16.16	9.55	13.21
H_2O at + 110° C.	.....			
Chromite	.....	.....	.57	.....
	100.78	99.94	100.38	100.22

1. Serpentine from a partly serpentinized dunite, nickel mine, Webster. The unaltered olivine is represented by analysis 4, Table 6. Forest A. Gonyer, analyst.

2. Serpentine from Corundum Hill. Frederick A. Genth, analyst; *Am. Jour. Sci.*, 3d ser., vol. 40, p. 308, 1890.

3. Serpentine var. williamsite from Webster. Frederick A. Genth, analyst; U. S. Geol. Survey Bull. 74, p. 63, 1891.

4. Serpentine (picrolite) from Webster. E. A. Schneider, analyst; Genth, Frederick A., *op. cit.* (Bull. 74), p. 63.

The foregoing analyses show that the nickel content of the minerals ranges from zero to a maximum of about 0.5 per cent. It is highest in the olivine; lower in actinolite, kammererite, and talc that replaced olivine; and absent or nearly so in the bronzite, green diopside, and chromite that are accessory minerals of the dunite and in the anthophyllite of the hydrothermal veins. Nickel seems to be lower in the serpentine than in the olivine from which it is derived. It is evident that nickel was highest in the intrusive material that gave rise to the almost pure olivine of the dunite. Nickel seems to have been practically absent in the hydrothermal solutions, and where these formed veins, minerals without nickel developed, but where solutions replaced olivine by actinolite, kammererite, and talc, a slightly reduced amount of nickel was carried over into the replacing mineral. The absence of nickel in bronzite, green diopside, and chromite suggests that these minerals crystallized from material that contained no nickel and therefore from a different magma than the dunite. Nickel can proxy magnesia and ferrous iron, and these magnesium or iron rich minerals could not crystallize from a material that contained nickel and be themselves free from nickel. The nickel content of serpentine is lower than in olivine, and this indicates that the solutions that altered olivine did not transport and concentrate nickel. Thus the pyrogenic mineral olivine is the only important primary mineral that carries nickel at Webster, and there is evidence that later hydrothermal solutions and the material that crystallized into websterite and chromite were not nickel-bearing.

NICKEL IN THE RESIDUAL SOIL.

The dunite has weathered to a deep-red porous residual soil with the following composition:

TABLE 12.

ANALYSES OF RESIDUAL SOIL FROM WEBSTER, N. C.[a]

	1	2	3
SiO_2	16.16	19.76	37.40
Al_2O_3	7.57	9.26	1.94
Fe_2O_3	46.34	56.69	14.38
Cr_2O_3	2.81	3.44	.42
FeO	.56	.68	1.16
MgO	6.14	7.53	28.64
NiO	1.80	2.20	1.88
CaO	.10	.12	.34
MnO	.26	.32	.08
H_2O at $-$ 110° C.	7.28	.....	5.96
H_2O at $+$ 110° C.	10.48	.....	7.68
	99.50	100.00	99.88

[a] Chromite was separated directly and weighed and the Cr_2O_3 calculated.

1. Red residual soil from nickel mine half a mile south of Webster. Forest A. Gonyer, analyst.
2. The same, recalculated to water-free basis.
3. Partly weathered dunite with porous texture and yellow color.

The analysis of the yellow, partly altered dunite shows that it has lost magnesia and silica, but the low alumina and iron content indicate that less than half the material has been removed by solutions, and the rock retains approximately its original volume. During alteration nickel has become about seven times as abundant as in the original rock. The partly altered dunite is a porous aggregate of amorphous magnesium silicates that are evidently capable of taking up nickel by base exchange. Therefore the initial weathering processes have resulted in a concentration of nickel.

The red residual soil contains 1.80 per cent. of nickel; the olivine from which it is derived contains 0.34 to 0.44 per cent. and the serpentine contains about 0.22 per cent. of NiO. These figures show that the nickel has undergone about as great a concentration as the iron and alumina. It seems probable that no great proportion of the nickel would be set free by the direct alteration of serpentine and olivine to this red residual soil, but complete alteration of the yellow material would yield nickel.

It seems probable, however, that most of the nickel has been set free from material that has completely disappeared except for the elements like nickel that were taken into solution and later redeposited. There has been very profound degradation in this region, and the nickel now found as nickel silicates must represent a very small fraction of all the nickel that was contained in the dunite that has been removed.

NICKEL-BEARING ROCKS FROM OTHER LOCALITIES.

Nickel has been found in a great number of olivine-bearing rocks, and it is interesting to compare their nickel content with that in the dunite of Webster. Table 13 shows a few of the analyses of such rocks that have been reported.

TABLE 13.

ANALYSES OF NICKEL-BEARING OLIVINE.

	1	2	3	4	5	6
SiO_2	43.27	37.80	42.81	38.97	40.01	40.68
Al_2O_3	.....	.....	.....	.....	.38	.....
Fe_2O_3	.....	.....	2.61	.....	.11	.....
Cr_2O_3	.....	.....	.79	.....	.....	.....
FeO	7.91	6.50	7.20	18.07	11.12	9.19
MgO	49.44	44.60	45.12	42.29	48.09	49.58
NiO	.11	2.43	.26	.18	.22	.50
CaO	None	Trace	.....	.....	.....	.02
MnO	.....	Trace	.....	.32	.....	.....
H_2O	.....	10.50	.....	.....	.....	.....
TiO_2	.....	.....	.....	.....	.12	.....
CuO	.....	.....	.....	.....	.....	.08
Loss on ignition	.....	.....	.57	.....	.....	.....
Insoluble	.....	.....	.....	.....	.....	.....
	100.73	101.83	99.36	99.83	100.05	100.05

1. Olivine rock (freshest obtainable) from New Caledonia. Glasser, M. E., Richesses minerales de la Nouvelle Caledonie: Extrait des *Annales des mines*, 2° semestre, 1904, et 1° semestre, 1904, p. 52, Paris, 1904.

2. Altered olivine rock from New Caledonia. *Idem.* p. 53.

3. Olivine from Douglas, Oreg. Clarke, F. W., *Am. Jour. Sci.*, 3d ser., vol. 35, p. 48, 1888.

4. Olivine from Itkul. Ural. H. Backlund, analyst; *Mus. Geol. St. Petersburg Travaux*, vol. 3, p. 94, 1909.

5. Olivine from Hawaii. War, F. W., in Dana, E. S., System of mineralogy, p. 453, 1909.

6. Olivine bomb from Stempel, near Marburg, Germany. Ch. Freidheim, analyst; Bauer, M., *Neues Jahrb.*, 1891, Band 2, p. 184.

Analysis 1 represents the freshest olivine that Glasser obtained for analysis from New Caledonia. Analysis 2 represents an olivine rock from the same locality. The fresh olivine contains only about 0.11 per cent. of NiO, and the serpentine contains 2.43 per cent. This New Caledonia olivine contains less nickel than the Webster olivine, but the serpentine contains much more. The nickel reported from the olivine is so low in view of the great quantities of nickel at New Caledonia that it seems doubtful whether this analysis can be representative. On the other hand, there is a strong possibility of a concentration of nickel in serpentine, and it is probable that these two analyses are not sufficient to show the nickel content of the original rock-forming minerals at New Caledonia. The available descriptions of the New Caledonia deposits are very inadequate and provide no basis for comparisons of paragenesis.

Analysis 3 represents olivine from Douglas, Oreg.,[16] where nickel silicates have developed.[17] The other analyses in the table are representative of many other analyses of nickel-bearing olivine that have been reported.

Serpentine, the common alteration product of olivine, usually contains nickel, but it is not necessary to reproduce here any of the numerous analyses that are available in the literature.

WASHINGTON, D. C.

[16] Clarke, F. W., U. S. Geol. Survey, Bull. 419, p. 270, 1910.

[17] Austin, W. L., "The Nickel Deposits near Riddle's, Oregon," *Colorado Sci. Soc. Proc.*, vol. 5, pp. 173–196, 1896.

GEOLOGY OF THE ST. FRANCIS DAM–SITE.

F. L. RANSOME.

THE St. Francis dam was situated in San Francisquito Canyon, about 45 miles north-northwest of Los Angeles and 9 miles north of Saugus. (See Fig. 1.) Its purpose was to form a storage reservoir into which surplus water was delivered from the Los Angeles aqueduct. The capacity of the reservoir was 38,000

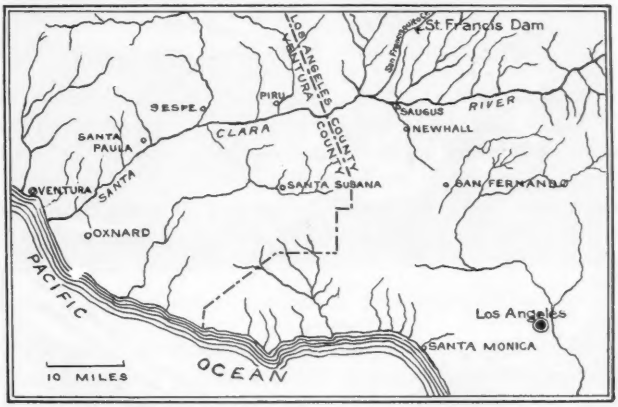

FIG. 1. Map showing the position of the St. Francis dam with reference to Los Angeles and the surrounding region.

acre-feet. About 9 miles below the dam San Francisquito Canyon opens into the broad fertile Santa Clara Valley which continues westward for 44 miles to the Pacific Ocean.

The dam (Fig. 4), completed on May 4, 1926, by the Bureau of Water Works and Supply, City of Los Angeles, was of solid gravity type and constructed of concrete. It was 205 feet in height and the main dam was 700 feet long. In addition, the

structure was continued northwestward by a wing-wall along the crest of the spur that formed the abutment at that end. The dam was curved, on a radius of 500 feet, the convex side being the upstream face.

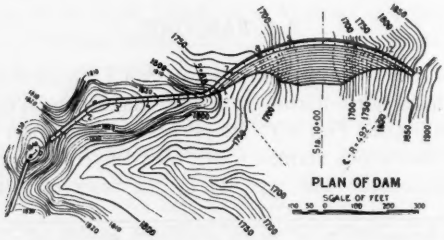

FIG. 2. Plan of the St. Francis dam.

San Francisquito Canyon at the dam-site has a course of south 60 degrees west. The walls, although steep, particularly on the southeast side, are not precipitous and are covered by the usual brushy vegetation of the Coast Range of Southern California. The bottom of the canyon and the slopes of the southeast side, as shown in Fig. 3, are underlain by mica schist, which in geological

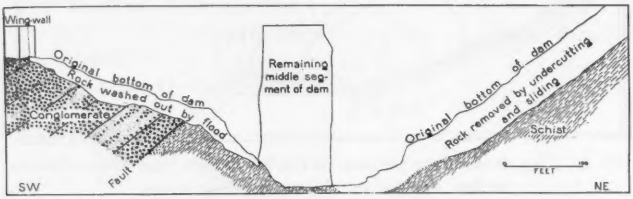

FIG. 3. Geological Section through the St. Francis dam-site.

reports [1] on the general region has been, with non-committal caution, designated as pre-Jurassic. The upper northwestern slopes are composed of a reddish conglomerate with sandy and shaly layers, which is probably of Sespe (Oligocene?) age. The con-

[1] Kew, N. S. W., "Geology and Oil Resources of a Part of Los Angeles and Ventura Counties, California," U. S. Geol. Surv. Bull. 753, 1924.

tact between the two rocks is a fault which has a course approximately parallel with the canyon and outcrops along its northwest side, about 70 feet above the bottom of the canyon, at the dam. This fault, a rather obscure feature before the tremendous flood caused by the bursting of the dam swept the canyon clean, is now plainly visible, a sharp line separating the dark conglomerate above from the lighter schist below. (See Fig. 6.)

FIG. 4. General view of completed St. Francis dam and reservoir.

The planes of schistosity, although variable in their attitude, strike, in general, parallel with the canyon and dip northwesterly at 50 to 60 degrees, or only slightly steeper than the prevalent inclination of the slope. Zones of shearing are numerous, and it is evident from the character of the slope, road-cuts, and tunnels that the schist as a whole is a fragile rock which readily disintegrates into thin flakes. Cohesion between the laminations is, as a rule, slight.

The conglomerate, probably a fresh-water deposit, is composed of poorly assorted schist, granite and sandstone detritus, which ranges from clayey silt to pebbles 8 inches or more in length. Bedding is generally rather indistinct and much of the formation

is covered with soil. High up the slope, above the dam, may be seen, however, rounded outcrops of conglomerate which suggest that a part of the formation, at least, may be fairly hard and moderately resistant to disintegration and erosion. The general dip of the beds is about 45 degrees, to the northwest.

The San Francisquito fault has long been known and appears on the fault map of California, compiled under the auspices of the Seismological Society of America, as an inactive or "dead" fault. There is no evidence that any recent movement has taken place along it or that movement was directly responsible for the failure of the dam. The dip of the fault-plane is to the northwest at from 35 to 40 degrees. There is a well-developed clay gouge, which is soft and plastic when wet and consists of two distinct portions. Next to the schist foot-wall is a layer of dark gray clay up to 8 inches thick, composed apparently of triturated schist. Overlying it is a reddish clay, up to 4 feet thick, which is plainly ground-up conglomerate, and grades upward into crushed and sheared conglomerate. All of the conglomerate, to an elevation at least equal to the crest of the dam, has been strongly sheared, this shearing being of such intensity that the pebbles themselves are minutely fractured and faulted. The character of movement on the fault is not definitely known. The fact that the younger conglomerate has been brought into a position in which certain of its beds abut against the schist suggests a normal fault. On the other hand, the extensive crushing of the conglomerate and the low dip of the fault-plane are indicative of overthrusting. The fault is probably an overthrust, although the structure of the region is not well enough known to permit of certainty on this point.

When dry, the conglomerate of the dam-site is fairly firm, although it is by no means a strong rock. A test, made for the State's investigating commission, gave a crushing strength of 500 pounds to the square inch, whereas the concrete of the dam has a strength of 2,000 pounds to the square inch. When wet, however, the rock shows a remarkable change. A piece about 2 inches in diameter taken from the northwest abutment of the dam

at a point directly beneath the former structure, when placed in a beaker of water begins to flake and crumble and in about 15 minutes slumps to the bottom of the vessel as a loose gritty sediment that can be stirred about with the finger. Evidently the particles of the conglomerate are held together merely by films of clay and when the mass is wet practically all cohesion is lost. Even the fractured and faulted pebbles fall apart into small fragments.

FIG. 5. The schist at the southeast abutment, as cleaned off for the concrete.

The conglomerate is traversed by many small veinlets of gypsum and it is probable that this mineral constitutes a part of the cement that holds the rock together when dry. The solubility of gypsum is well known, and the presence of this mineral probably contributes to the rapid disintegration of the mass when wet.

The dam obviously was built across the fault. (See Fig. 3.) The southeast end and the middle section rested on schist. The northwest end, including the wing wall (See Fig. 6) rested on conglomerate. At the southeast abutment the concrete rested against smooth cleavage surfaces of the schist, and although the concrete adhered to these surfaces, the schist itself offered little resistance to stresses that might tend to pull the dam away from

its abutment or to move it in directions generally parallel with the planes of schistosity. The middle section of the dam, which is still standing, rests on the edges of the schist, and is obviously on a much stronger foundation than were the end sections. The northwest end of the dam abutted against and rested on a rather narrow spur of conglomerate. As already shown, this material, when wet, provided no better foundation than so much muddy sand.

So far as can be ascertained, no geological examination was made of the dam-site before construction began and no crushing or immersion tests were made of the conglomerate. How the true nature of this rock failed to become apparent during the progress of construction is difficult to understand.

The reservoir first became full about March 5, 1928. Some seepage was noted through the conglomerate of the northwest abutment and evidently caused some concern to those responsible for the maintenance of the structure. They appear, however, to have had no adequate conception of the full significance of this indication that the conglomerate had become water soaked. Chemical analyses made, since the dam failed, of water taken from the Los Angeles aqueduct and from places where seepage water from the reservoir was still flowing from the conglomerate, show a remarkable contrast in soluble constituents. The CaO and SO_3 radicles particularly are many times higher in the seepage water than in the aqueduct water, showing that active solution of gypsum and other constituents was taking place in the conglomerate. This suggests that in future examinations of dam-sites, clastic rocks, concerning whose cementing material there may be any question, should be subjected to leaching tests with chemical analyses of the extracts.

Quite aside from any possibility of movement on the San Francisquito fault, it is plain that the dam, otherwise a well-designed and well-built structure, was planned without adequate knowledge of the geological features of the site and without proper consideration of the structure and materials of the rocks upon which it was to rest.

FIG. 6. St. Francis dam after the failure. To the left of the standing segment the lighter colored schist below the San Francisquito fault is plainly distinguishable from the darker conglomerate above the fault.

It is probable that the dam failed initially at its northwestern end. As the conglomerate became water-soaked, the cementing

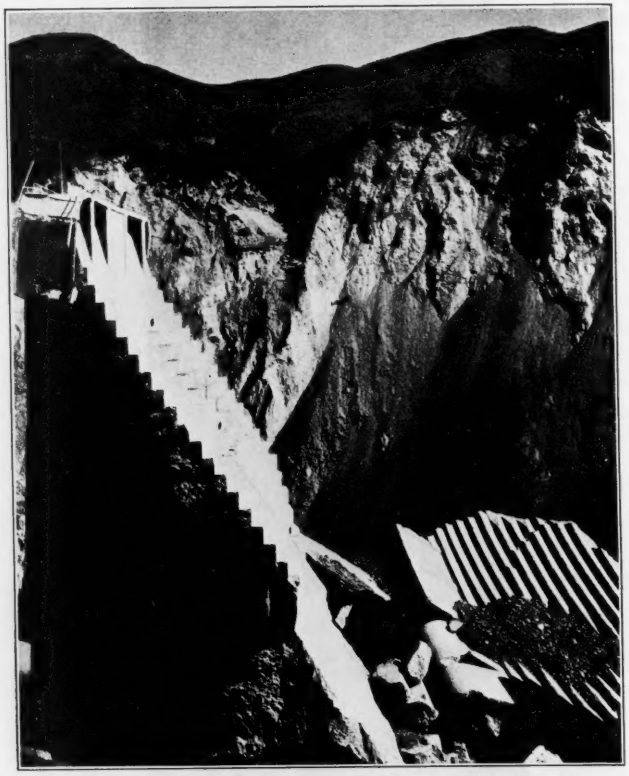

FIG. 7. The southeast abutment, after the failure, showing talus due to the undercutting of the schist-layers.

clay and gypsum were softened and dissolved. The supposed rock upon which that part of the dam rested lost practically all of its strength and became no better suited for a foundation than a

mass of wet earth or gritty clay. Seepage through this material probably increased rather suddenly to a jet of water which, rapidly attaining appalling proportions, washed out the softened

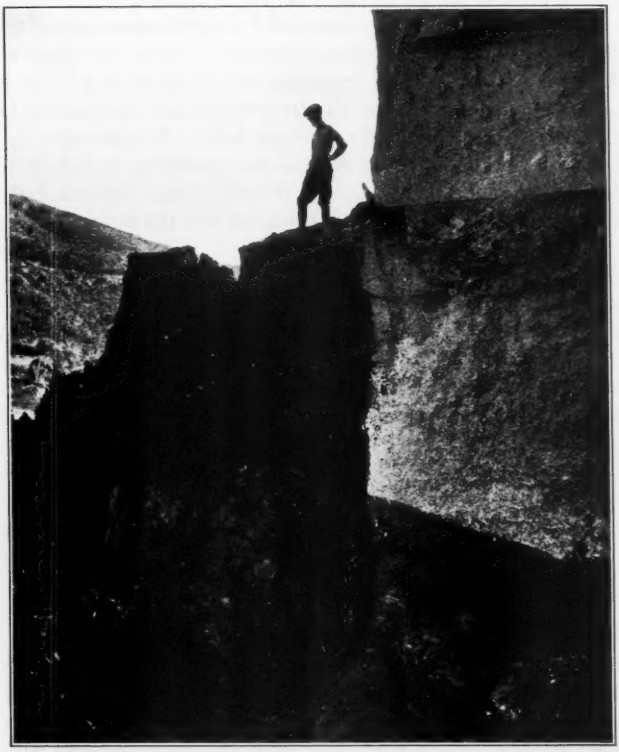

FIG. 8. The conglomerate under the wing-wall at the northwest abutment.

conglomerate, permitting the concrete to crack and then to be swept out in huge blocks, up to 10,000 tons in weight, which were distributed for half a mile down the canyon. The terrific swirl of water about the toe of the dam undercut the layers of schist

at the southeast abutment and probably within a few minutes of the opening of the first breach, the entire southeastern end of the dam slid down into the canyon, the largest fragment coming to rest against the toe of the standing middle segment.

The commission of engineers and geologists appointed by the Governor of California to investigate the causes of the disaster [2] found no evidence of any recent movement on the San Francisquito fault and ascribed the disaster wholly to the unsuitability of the material upon which the dam was built. A commission appointed by the City of Los Angeles and consisting of Robert T. Hill, C. F. Tolman, and D. W. Murphy, while confirming the conclusion of the Governor's commission that the principal cause of the failure was the character of the rocks under the dam, states that a check of the elevation of the standing wing-wall shows it to have risen 0.285 feet since the dam was constructed and suggests that this apparent uplift may have been caused by movement on the San Francisquito fault. This movement, the city's commission believes, may have contributed to the failure of the structure. Whether the engineering data are of sufficient accuracy to prove the small uplift of approximately 0.3 foot is questionable. In any case, however, failure of the dam was inevitable in consequence of the weakness of the conglomerate under its northwestern end. Even had that portion been able to withstand the pressure of the water in a full reservoir, it is highly probable that the schist at the southeast abutment would have ultimately failed.

A conspicuous feature of the reservoir after the failure of the dam was the occurrence of landslides, principally on the southeast side, just above the dam. (See Fig. 7.) These slides evidently took place after the rupture of the dam and were in no way responsible for the failure of the structure. The original slope was steep and stood at nearly the maximum angle consistent with the inclination of schist-layers. As the reservoir filled, this ground became watersoaked and with the sudden removal of the pressure of the water in the reservoir it slumped down into the canyon.

[2] Report of the Commission appointed by Gov. C. C. Young to investigate the causes leading to the failure of the St. Francis dam. Sacramento, Cal., 1928.

The plain lesson of the disaster is that engineers, no matter how extensive their experience in the building of dams or how skillful in the design of such structures, cannot safely dispense with the knowledge of the character and structure of the adjacent rocks, such as only an expert and thorough geological examination can provide.

CALIFORNIA INSTITUTE OF TECHNOLOGY,
PASADENA, CAL.

EDITORIAL

BIBLIOGRAPHIES, ANNOTATED BIBLIOGRAPHIES AND GEOLOGICAL ABSTRACTS.

It is not necessary to argue at great length regarding the desirability of keeping posted on what is going on the science of geology. No doubt everyone admits it "in principle." Almost everyone has probably had unpleasant experiences in overlooking data already in the literature or needlessly repeating descriptions already in existence. It has become more and more difficult to master the literature even in one's own specialty and in one's own country. When it comes to foreign literature the difficulties and possibilities of error increase, for we as a nation are little given to linguistic accomplishments, and to a large proportion of us it is somewhat of a hardship to read rapidly accounts in a foreign language. There is also a certain apathy among geologists as to what is going on in foreign countries. Many of us are too busy with our own detailed work to pay much attention to foreign periodicals and, indeed, it is difficult even for those well versed in languages to do so.

Other sciences have experienced the same trouble but some of them, unlike ourselves, have overcome it by adequate abstract journals. I refer particularly to the chemists, whose publication "Chemical Abstracts" is well and favorably known. It is less well known that these chemical abstracts are published by the American Chemical Society at an expense of $107,000 per year, the money being obtained from the membership fees of the Society. In biology a similar issue is called "Biological Abstracts," published in monthly issues at a cost of $60,000 a year for the editorial work alone. The funds for this are obtained from grants of the Rockefeller Foundation.

Compared to these successful enterprises the efforts of the geologists in this country to keep abreast of the times do not stand

out in an enviable light. It is true that the number of geologists compared with that of chemists and biologists is small; but on the other hand the number of publications to be reviewed is also comparatively small.

Four or five years ago Professor Lawson, then chairman of the Division of Geology and Geography of the National Research Council proposed to raise a fund of $200,000 for "Geological Abstracts"; it was held that this would yield an annual income of $10,000. The effort was not successful owing to lack of interest. The sum eventually pledged was less than a tenth of the sum required.

Let us look over the field and see what the United States and the world at large have to offer at present in the way of geological bibliographies and abstracts. But it must be borne in mind that abstracts and bibliographies in a foreign language will not fill the want for this country, for the simple reason that geologists as a rule will not or can not use them. What is the actual position as to abstracts in the science of geology? From the last report of Dr. Edward B. Mathews, chairman of the Committee on Abstracts and Bibliographies of the Division of Geology and Geography of the National Research Council, I take in part the following data:

Publication.	*Approximate Number of Abstracts or References.*
Bibliography of North American Geology, U. S. Geological Survey, Washington, D. C. (published every other year), whole field	1,350
List of accessions of the Library of the Geological Society of London (published annually), whole field	4,000
Bibliographie des sciences géologiques. Published by the Geological Society of France and the French Society of Mineralogy (tri-monthly), whole field	4,000
Geologisches Zentralblatt, Leipzig (semi-monthly; abstracts), whole field	2,914
Neues Jahrbuch f. Min., Geol. und Pal., Stuttgart (bi-monthly; abstracts), whole field	2,700
Revue de geologie et des Sciences connexes, Liège, Belgium (monthly), abstracts; geology, crystallography, mineralogy	1,660

The first three publications are simply bibliographies; the last three give short abstracts of the articles or books listed. In addition to this there is in this country a more or less incomplete bibliography on economic geology published by the American Institute of Mining and Metallurgical Engineers. Abstracts of important contributions are published by the Journal of Geology, Economic Geology and the American Association of Petroleum Geologists, and by most of the foreign geological journals. None of these makes a pretense to completeness. In addition many European countries issue bi-monthly or annual lists of their own geological literature.

The Bibliography of North American Geology is fairly complete as far as this continent is concerned. The other bibliographies and abstract journals are decidedly incomplete as to American geology. Even if the foreign publications are utilized it is difficult to obtain a complete orientation, and if not, the geologist in search of information is hopelessly at sea.

Conditions being as they are, what should be done? There is some doubt as to whether $10,000 per annum would cover the cost of permanent geological abstracts, but even if it would be sufficient, how could the sum be raised? Direct appeal to geologists did not bear fruit. The government, meaning the official surveys and bureaus concerned, might do it but would they or could they? Private generosity might be appealed to, but the great mining and oil companies of the country have not been inclined to contribute great sums to geological science, great as its services to them have been. Two of the great funds to advance research give generously to many sciences but do not include geology. Conceivably they might contribute one half, leaving to geologists the task of getting together the other half. And geologists are evidently not experts at the task.

It appeared to a small group of economic geologists that instead of sitting around like the Israelites waiting for manna to fall from heaven, it might be better to make an attempt to help themselves. This group consisted of E. DeGolyer, H. F. Ferguson, D. F. Hewett, W. Lindgren, G. F. Loughlin, W. C. Mendenhall and R. A. F. Penrose, Jr.

It was decided to attempt to raise money to carry on an "Annotated Bibliography of the International Literature of Economic Geology," at least for a number of years; confidence was expressed that the publication would prove so beneficial that after some years means would be more easily found to continue it indefinitely and perhaps expand it to include all branches of geology. An "annotated" bibliography means a list of publications with a short, concise statement of the chief points of interest of the new books and articles.

The plan includes a subscription fund of from $18,000 to $24,000 which will provide means for the editorial work for from five to seven years. The National Research Council has agreed to serve as treasurer and custodian of these funds to be expended in accordance with the usual customs of the Council. Tentative arrangements have been made with an experienced bibliographer to take charge of the work. The Economic Geology Publishing Company has agreed to publish the bibliography, which is to be issued in two volumes per year, aggregating about 400 pages, and to sell it for an equitable price, probably about $2.50 per volume, which should pay for paper, printing and distribution. The subjects to be covered include articles on all metallic and non-metallic deposits (including petroleum and gas), hydrology, engineering geology and soils (in so far as related to geology). Publications in other branches of geology will be included if they have any bearing on economic geology.

It has been suggested that the bibliography should be published bi-monthly instead of semi-annually. Perhaps this would be better but it would considerably increase the expense, and the expense is certainly an item just at present. A complete cross index with every number will facilitate the looking up of references.

A circular was sent out to about 1,000 men chiefly interested in economic geology, and to about 200 mining and oil companies. A pledge was asked for, payable if desired in three annual installments, the money not to be called for until the minimum sum of $18,000 had been subscribed.

Two months have passed since the first appeals were sent out

and it is interesting and instructive to observe the results. Half of the desired minimum has been reached, *i.e.*, $9,000. Several mining companies and oil companies have subscribed generously —seven to date. But of the 1,000 individuals appealed to, all of whom were supposed to be vitally interested in economic geology, only 64 have responded, the contributions varying from $5.00 to $1,000, with a total of about $5,300.

I think there is no doubt that the sum required will be reached; it will take some effort, however. But the facts set forth furnish abundant food for thought. It would seem a fair conclusion that the majority of economic geologists are not interested in the plan —at least not enough to contribute, however small the amount. It doubtless indicates a lack of appreciation of the necessity of keeping abreast of the times, of the need of ascertaining what other investigators in other countries are doing.

This editorial is therefore an earnest appeal to the economic geologists of this country and Canada to do their share, large or small, by sending in their pledges to the Division of Geology and Geography of the National Research Council, Washington, D. C., and also to attempt to interest their companies in the plan, for the efficiency of the staff is largely dependent upon familiarity with the progress of geological science throughout the world.[1]

A committee of five on a bibliography of economic geology is now regularly organized in this division of the National Research Council, and will carry on the plan as outlined. These men are willing to pledge money and work on their part if they are confident that the economic geologists of the country stand behind them.

WALDEMAR LINDGREN.

NATIONAL RESEARCH COUNCIL,
B AND 21ST STREETS,
WASHINGTON, D. C.

[1] Those who desire regular blanks to make a subscription may obtain them from the Editor or from Waldemar Lindgren.

DISCUSSION AND INFORMAL COMMUNICATIONS

THE OPENING AS A REASON FOR ORE.

Sir: An editorial by Augustus Locke under the above heading (ECON. GEOL., Vol. XXIII, No. 1. Jan.–Feb. 1928) presents some stimulating and unique viewpoints. In critically discussing some of the statements I do not wish to appear unappreciative of the writer's theme, which is one to which attention should be drawn more often than is now the case in geological literature.

After picturing a fascinating but speculative mechanism which " is the general action which includes ore formation," Mr. Locke concludes that " an obvious feature in the formation of most ore bodies is a release of pressure by an opening of the rock extending all the way up to the surface," together with an " equally vital and equally common (feature), namely, the growth of that opening during the movement of fluids through it, by the removal of rock volume in excess of the mineral volume deposited." An implication therefore is " that the ore body is made under a leaky, not under a tight cover." Also, pressure of the metal-bearing fluids " will be made up mostly of the weight of the column of moving fluid."

In my opinion such conceptions have dubious application in many important ore bodies. For a large number of gold-quartz and sulphide ore bodies that lie in shear-zones a picture of a column of moving fluid with open cracks above, extending to the surface, is inconceivable. To form ore bodies in these shear-zones the ore solutions have penetrated numerous avenues, laterally, horizontally, even inclined downward, as well as vertically or steeply inclined upward. They have thoroughly permeated the rock in many instances and often have extensively replaced the rock. The present form of the ore body is mainly a composite re-

sult of two major processes, namely penetration and replacement. In permitting penetration, openings have been an extremely important factor. But many are definitely limitable within our view far below the present surface. Movement has certainly not been in a vertical direction in many special instances. Penetration has obviously been at any angle to the earth's surface. A notion that the ore deposit was connected with the surface by open cracks, during its formation, might be entertained if we visualize a series of complex openings, however small, forming tributaries with open cracks, real or imagined, at a lateral distance from the ore body. But in many cases this is purely notional. We actually see many components of the ore body, or the ore body in its entirety, limited in all directions, as determined by observation or by mining, well beneath the earth's surface, and we can frequently trace the ends of the individual openings that determined the site of the mineral body. Ore solutions have manifestly penetrated laterally and circulated insinuatingly in many cases. This destroys the reality of our picture of a rising column of ore fluids seeking release of pressure through openings to the surface.

At Cobalt, Ontario, the tops of some veins which lie in narrow sharply defined fissures, are separated from even the present earth's surface by hundreds of feet of rock of pre-ore age. It is extremely improbable, if not inconceivable, that these vein fissures ever communicated with the surface. At Porcupine, Ontario, many ore bodies are "blind" (not outcropping) and whatever connection the vein and lode fissures may have had with the surface during ore formation, must have been through extremely circuitous routes. Quartz lodes follow fissures with numerous diverse components. Many veins and veinlets penetrate fissures measureable by a few feet or a few hundred feet. The limits of these fissures can be traced in every direction and may not reach within thousands of feet of even the present surface. Flat or nearly horizontal ore bodies such as some gold-quartz veins in northwestern California and the Buchans sulphide ore body here in Newfoundland, show that, given the proper structural conditions, ore solutions will seek a horizontal path. They may, in

fact, seek any path regardless of its attitude with respect to the earth's surface. They do not require a connection with the earth's surface such as Mr. Locke says is an obvious feature of most ore bodies. They do require an impelling force, which can be found in hydrostatic and vapor pressure of the ore fluids without assuming "a pressure made up mostly of the weight of the column of moving fluid."

However important the removal of rock volume in excess of the mineral volume deposited has been in the instructive examples Mr. Locke has brought to our attention, it is still far from proven that this is a characteristic feature of ore deposit. Three conditions exist: first, a deposition of mineral volume in excess of the rock volume removed, a common case; second, a deposition volume for volume or nearly so, which appears to be extraordinarily common; and third, a deposition of mineral volume less than the rock volume removed. In general geologic processes, all three conditions take place depending upon geologic environment and forces, and the same holds true for the special case of ore formation. In many instances the story is assuredly not told by imagining a sponge-like enlargement of the original conduit "with ore containing wide-spread vugs and cracks and a porosity thousands of times as great as that of the rock which it replaces." In many massive sulphide ore bodies the reverse is obviously true. Here in Newfoundland there is a massive zinc-lead-copper sulphide ore body, so compact, dense, and fine-grained that its texture has been aptly termed "razor hone." Some of the associated country rocks are by comparison quite porous. There is here, and in a number of other massive sulphide aggregations, no evidence that ore formation involved a removal of rock in excess of the ore formed.

The implication that ore bodies are made under leaky rather than tight covers is true for some, but inconceivable for others. Among the latter are gold-quartz veins of deep-seated origin; flat sulphide bodies beneath impervious rock mantles; magnetite replacement bodies beneath or in limestone; sulphide and magnetite aggregations in some massive igneous rocks. In discussing

the conception of open fissures to the earth's surface, I have cited some special examples in which the ore was clearly formed under a tight cover. The literature of ore deposits contains a number of examples of ore localization beneath tight covers and I think most observers in mining geology can list a number from personal observation. Lindgren, and others have given us a genetic classification of ore deposits based upon the physical conditions that existed during ore formation, in which relative pressure and relative depth beneath the earth's surface are extremely vital factors in determining the kind of ore deposit. Perhaps Mr. Locke can conceive of ore deposits formed through a vertical range of several miles and with striking mineralogical and structural variations all coming under the head of deposits produced under a leaky cover. But there is no more justification to assume this than to assume that siliceous sinter and the quartz of granite are produced in the same geologic environment. Comparison of such deposits as the gold-quartz veins of deep-seated origin with quicksilver deposits of near-surface origin, brings out striking structural differences which arise mainly from the fact that the gold-quartz bodies were formed under thousands of feet or miles of rock, whereas the quicksilver deposits were of shallow origin and may, indeed, have been produced under a leaky roof.

Mr. Locke's statement that " the increase in porosity and therefore of accessibility, which we find in all but a few cases, is the only known means by which, through the travel of low gravity fluid along cracks, the concentration which we term an ore-shoot can be formed " challenge criticism. In order that low gravity fluid, or any other kind of ore fluid, can travel along cracks it is simply necessary that the force or forces impelling mobility shall be in excess of the force or forces restraining mobility. Increase in porosity is certainly not the only means by which this condition can be brought about. I am of the opinion that ore shoots are formed by fissure filling along cracks, with or without replacement, and frequently without any increase in the porosity of the invaded rock either by mineralizing forerunners of the ore-depositing solutions or by these solutions during ore deposition.

One of the remarkable features of many ore deposits formed in deep-seated and intermediate depths is the manner in which the ore minerals have penetrated through dense rocks. There are a number of mechanisms whereby this penetration is possible and an ore body may result, without an increase in porosity as an essential feature. Yet it is possible that this increase in porosity exists in many cases where it has been overlooked or its importance has not been sufficiently emphasized.

When one critically examines the attempt to explain certain features of ore deposits as a result of "openings reaching the surface and supplying to the rock along the way a metal-bearing fluid which alters the rock with increase of porosity" numerous objections arise. It is surprising, for instance, to have this given as a basic reason for the proximity of many mineral deposits to igneous intrusions, a universal condition but of wide variation. We find the ore deposits assuming all possible positions with respect to the associated intrusives, over, under, alongside of, within, entirely without, partly within and partly without. Each deposit presents its peculiar problem in ore localization. In many cases a notion of open fissures to the surface can only be entertained if we go to the small or great lateral distances from the site of ore deposition to look for these possible fissures. One general fact is outstanding, namely, that intrusives and the associated ore bodies characteristically seek the same locus in the earth's crust. And one general conclusion is perhaps justified, namely that springing from the same source and at nearly or quite the same time, any factor or series of factors that cause the intrusives to seek some locus will likewise cause the ore depositing solutions, migrating approximately contemporaneously, to seek this locus. One general explanation of the localization of intrusives and ore bodies is that they both seek loci of easiest penetrability. To the extent that openings to the surface may supply these loci these openings may account for the association of intrusives and ore deposits, the depositing solutions both having moved to a region of easiest penetrability. But in many cases one will not go far in solving the problem if one is content with an explanation of a

convergence of the intrusives and ore-carrying agents toward a region of smaller pressure due to opening reaching the surface, because one will be beset with many contradictions. For instance, such an explanation cannot explain the preference of some intrusives and ore deposits for limestone zones. Mr. Locke has mentioned this preference and suggests that it " is seen to be due to their (calcitic and feldspathic rocks) particular brittleness and strength and at the same time to their capacity for alteration with increase of porosity." Manifestly, the physical and chemical nature of calcitic rocks determine notable ore localizations and the features mentioned are some of these. But these features are independent of the mechanism Mr. Locke sets forth. Limstone that was deeply buried during ore formation, as for instance during many magnetite concentrations of western North America, was particularly susceptible. This same limestone may also be unusually susceptible to dissolution by present near-surface ground waters. Inherent physical and chemical properties explain this susceptibility under such widely differing conditions. It must be clear that these characteristics may explain ore localization quite independently of the fundamental mechanism Mr. Locke has visualized for us, however conceivable such a mechanism may be in certain cases.

Reverting now to the main theme of Mr. Locke's editorial " The Opening As a Reason for Ore," let us examine carefully the premises : First, consider the reasons for the entrance, or passage through, of ore-depositing solutions in one place rather than another. This I would define as a function of penetrability, that is the susceptibility of being entered or passed through by another body. Now, in this penetrability the relative openness of one rock as compared with another is undoubtedly the major factor. It may be set down as generally true that the more open the rock the more readily it is penetrated. But it by no means follows that penetrability is the fundamental reason for the localization of an ore body in one place rather than another. We must constantly bear in mind two major questions: (1) What has caused this or that rock to be penetrated by ore-depositing solutions. (2) What

has caused ore emplacement during or after this penetration. When ore is in vugs, or lines open fractures, or is deposited at the orifices of cracks, or lines brecciated fragments, or forms crystallized aggregations in fissures so there is little or no doubt that open fissure filling was the major mode of formation, we might say that openings are the immediate tangible reason for ore localization. Yet even in these cases the reasons for deposition in a particular locus along these openings are not faced if we look upon the opening itself as sufficient reason.

The second of our two major questions remains to be answered. When we find certain sulphides seeking out certain minerals in igneous and metamorphic rocks and preferentially replacing them, and also find unfilled fissures of pre-mineral age nearby, we are facing a contradiction if we hold that openings determine the position of the sulphides. Localization of ore beneath or along relatively impervious rocks, shear planes and gouges, far from showing that an opening is the reason for ore formation, indicates that lack of an opening induced ore deposition. Here the ore forming solutions were impounded, their mobility impeded. This is the tangible reason for many ore localizations, I believe, however obscure the fundamental ultimate reasons may be. When gold-quartz veins pass from one rock to another the gold tenor may abruptly change. This may take place without change in structure or if there is a change in structure, without evidence that the more open rock induced the greater gold deposition. Under all structural variations the gold tenor may show the same abrupt change. Here, then, is an example of the localization of an ore body where the opening is not the immediate reason for ore. The localization of magnetite bodies in or near limestone without visible structural control is common. Openings in the limestone or its alteration with increase of porosity become unintelligible reasons for magnetite localization in various igneous rocks contiguous to the limestone. Rather one must look upon the vigorous interchange of material between the limestone and the igneous rock as the vitalizing mechanism. The formation of the magnetite and its localization becomes, therefore, essentially a

physico-chemical problem. Replaceability of one rock as compared with another is apparently of great importance in many cases of important ore deposits. Nor does it appear that this replaceability is always a function of the openness of the favorable rock as compared with the unfavorable one. For instance we may find a highly sheared quartz porphyry containing scanty sulphides and a massive, relatively tight and poorly fissured greenstone with dense sulphide concentrations.

From these few random examples it is clear that we often cannot regard the opening as the immediate tangible reason for ore localizations. The relative porosity of one rock as compared to another is a fundamental reason for penetration by ore depositing solutions through or into one place rather than another. Strictly speaking, the opening is merely a means to an end, and even in those simple cases of filling, the immediate reason for precipitation in one place rather than another along these openings remains to be discerned.

We must not lose sight of the fact that the immediate tangible reasons for ore localizations are not the ultimate reasons. These ultimate reasons depend upon natural laws. It is true they are intangible. They are part of the ultimate causes of all things. We see light occasionally but the problem is infinite.

Mr. Locke's ideas, laying stress upon the importance and prevalence of volume loss as an essential part of the mechanism of most ore deposition, in contrast with the ideas of Spurr and Taber, emphasizing the efficiency of fluid pressure with the force of crystallization, inspire meditation upon the trend of the science of ore deposits. Why do we find capable workers in this field so much at variance? Psychological factors are partly responsible but I believe that the endless variability of ore deposits accounts for a large part of the diversity of opinion. If we are to maintain a proper outlook on ore genesis we must keep a mental picture of the whole panorama while concentrating attention upon the immediate problem. In the field of thermal deposits we must consider the numberless variations between such extremes as the effluences of surface springs and the plutonic aggregations. It

must follow that there are radical differences in the mechanism of ore deposition, under the widely differing environments.

It seems probable that most or all rational theories are true in particular even if exceptional cases, and some are undoubtedly true in numerous cases. But invariably the zealous advocate of conceptions of ore genesis widens his field too far, and those who put these conceptions to the test find inevitable contradictions. Underground, where one is brought closest to the ore deposits, I have repeatedly looked for conclusive evidence supporting the notion that fissures are widened by pressure during ore formation. A bending of such rock as schist or slate outward in conformity with a vein has suggested this force in a number of instances. Yet if one finds the edges of the fissile rock crosscut in places, without contortion, doubt arises that the bending was caused by vein growth and there is more reason to believe that the bending antedated vein formation. Failure to find undisturbed cross-cutting relations still leaves the problem unsatisfactorily solved because the thought persists that such conditions may exist but the particular exposure is not extensive enough to disclose them. Penetration of the distorted rock by vein minerals in alignment with the distorted planes of fissility raises doubt that the distortion was caused by vein growth and furthers the conclusion that the vein minerals followed preëxistent foliations in the rock. In all cases one must carefully consider the probability of post-mineral deformation. My observations so far have not disclosed convincing evidence that vein growth deforms the enclosing rock. But this does not mean that pressure was not exerted upon the walls of some veins by the vein material. Pressure certainly promoted penetration, may have been extremely efficacious in promoting dissolution of the wall rock in many instances, and may also have pushed aside the enclosing rock in some cases, even though there is now no discernible evidence that this occurred. I am satisfied that the force of crystallization during natural mineral growth, is a reality, but evidence that this force distends vein walls on any important scale has not been found. One striking instance of the reality of the force of

crystallization was observed, at Porcupine, in which schist was bent around the corner of a large pyrite cube. But such rare examples only emphasize the absence of any clear evidence of deformation of the enclosing rock along the vast majority of mineral bodies. Mr. Locke's stressing of volume loss during ore formation has important local application but as far as my observation goes it is not an essential feature of many ore deposits though present locally in practically all. Volume for volume replacement, or nearly so, has been observed numerous times and on a very large scale and appears to be the main mode of formation of many large mineral bodies, however difficult it is to explain the details of the process.

ELLSWORTH Y. DOUGHERTY.

ST. JOHNS, NEWFOUNDLAND.

AN OCCURRENCE OF SCHISTOSE GALENA.

Sir: A brief description is here given of an occurrence of galena ore having exceptionally well-developed secondary textural features. Secondary deformation in sulphide ores has been described by several writers,[1] but the following description may be of special interest because of the unusual fineness of grain and distinct schistosity in much of the deformed ore. The term

1 Ransome, F. L., and Calkins, F. C., "The Geology and Ore Deposits of the Coeur d'Alene District, Idaho," U. S. Geol. Surv. Prof. Paper 62, pp. 91, 108, 112, and 168, 1908.

Emmons, W. H., "Some Regionally Metamorphosed Ore Deposits and the So-called Segregated Veins," ECON. GEOL., vol. 4, pp. 755–781, 1909; "Some Ore Deposits of Maine and the Milan Mine, New Hampshire," U. S. Geol. Surv. Bull. 432, 1910.

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Emmons, W. H. and Laney, F. B., "Geology and Ore Deposits of the Ducktown District," U. S. Geol. Surv. Prof. Paper 139, 1926.

"schistosity," as here used, implies the development of an apparent flow texture, but without flow cleavage.

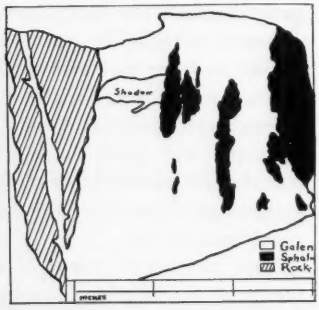
The Noche Buena (Christmas) mine, the source of the ore, is situated in the low hills bordering the western side of the Sonora Valley, near Camou, Sonora, Mexico, some 90 miles south of the international boundary and about 70 miles east of the Gulf of California.

The ore deposit occurs in a dike-like body of fractured and sheeted quartz monzonite which is surrounded by granite and granodiorite. The typical primary ore is coarse-grained, massive and irregular in form, without druses, and evidently deposited in large part through replacement of quartz monzonite. Oxidation has been slight. The principal ore minerals are galena and argentite (?), with which are associated considerable sphalerite, and some chalcopyrite. Argentite in finely divided particles disseminated through the galena is determinable in some polished specimens and is probably the chief source of silver derived from the ore.

Two varieties of galena of much finer grain than the typical ore occur irregularly throughout the deposit. One variety, a fine-granular (steel) galena, is found in the vicinity of minor slips and in association with coarser galena that shows lamellar twinning. A gradational change in grain size from coarse to fine is readily noted; the lamellae of the coarser material are increasingly curved and broken as it merges into the "steel" variety, and the whole assumes a rudely banded or gneissic texture. It is quite obvious that pressure must have produced first, the lamellar twinning and second, the deformation and ultimate crushing of the lamellae to form the finer-grained material.

The second variety of fine-grained galena, and the one of most importance from the standpoint of unusual textural and structural features, is of extremely fine grain—cryptocrystalline for the most part—and much of it exhibits a pronounced schistose or flow texture. The flow-lines or bands rarely exceed one-half millimeter in thickness and are often so narrow as to be almost imperceptible; they are never perfectly uniform or straight, and

are seldom distinctly continuous for more than an inch or two at most—tending to feather out against or merge into adjacent bands. Around inclusions the flow-lines are gently curved or occasionally abruptly so, and not infrequently abrupt bends occur where no immediate cause can be observed. Cleavage faces and striations are imperfectly displayed at irregular intervals along some of the wider bands, but in general cleavage is not apparent and the flow-lines are more aptly described as fine-grained streaks.



FIGS. 1 AND 2. Photograph and tracing of fracture surface of schistose galena ore showing relationships between galena, sphalerite and wall rock, also (Fig. 1) the finely schistose nature of the galena.

In color, this galena is a much lighter shade of lead-gray than the normal variety. It contains numerous segregations of black sphalerite in elongated forms oriented parallel to the schistosity. The sphalerite clearly appears to have been crushed and re-cemented. Chalcopyrite and its alteration products are conspicuously absent. Inclusions of wall rock are present in many places, and these also conform to the schistosity of the ore. The accompanying illustrations (Figs. 1 and 2) show these relationships and the photograph (Fig 1) shows also the finely schistose character of the galena. The fine-granular nature of the galena can be closely duplicated experimentally by compressing in a "diamond" mortar a small quantity of dry coarse-granular

galena crushed to pass a 200-mesh sieve. This schistose galena occurs in narrow seams and stringers and in lenses ranging up to eighteen inches in thickness; it is found only along major slips or fault planes, and is associated with crushed, partially altered quartz monzonite and chloritic gouge. The lenses and seams, and the schistose structure of the ore are all in alignment with the evident planes of movement in the wall rock.

The silver content is not noticeably higher in the fine-grained galena, as Ransome found to be the case in certain Coeur d'Alene ores,[2] but is rather irregular in its distribution.

The relationships between texture and structure of the deformed ore and the larger structural features of the deposit clearly indicate that the deformation was due to faulting, resulting from shearing stresses as well as from pressure. That differential pressure and resulting shearing were the chief factors in the production of the extraordinarily fine-grained, schistose galena can hardly be questioned. The schistose texture and the arrangement of sphalerite and wall-rock inclusions within the schistose material strongly suggest that the galena of the original orebody acted as a plastic mass, being deformed and pressed or squeezed out into its present condition by the dynamic movements. The fine-granular condition of the galena, the fineness of the flow-lines—most of which appear as streaks consisting of minute galena grains—and the slight evidence of cleavage further suggest that the deformation, instead of resulting from plastic flow in the sense of translation or twinning, or from granulation and re-crystallization, is largely the result of plastic flow like that of clay.

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[2] *Op. cit.*

REVIEWS

Theory of Continental Drift: A Symposium. By VAN DER GRACHT and others. Pp. 240, figs. 29. Amer. Assoc. Petr. Geol., Tulsa, 1928. Price, $3.50.

This little book should be a welcome addition to the library of all geologists. It treats of the various drift theories that have been proposed to account for the present distribution of the continental masses, indirectly discusses the nature of the earth's interior and incidentally deals with the mechanical consequences of its physical characteristics. A great volume of information is contained on its pages, most of which is of the kind that is difficult to find in the ordinary textbook. Taylor's, Wegener's, Daly's and van der Gracht's theories of continental drift are examined in detail, and the arguments for and against each are presented.

The introductory paper by van der Gracht is particularly interesting, as it outlines in a clear and forcible manner the principles underlying each theory and balances the evidence for and against the general conception of continental drift. Van der Gracht's conclusion is 'that an ever accumulating amount of evidence is piling up in favor of continental drift,' but 'it remains very difficult to explain the mechanism of the impulses which caused it.' 'It is probable that the main controlling factor is time.'

The discussion is continued by R. D. Chamberlin, Willis, Schuchert, Longwell, Bowie and Berry, who contend that there is not sufficient evidence to warrant a belief in the fact of 'continental drift'; by Joly, G. A. F. Molengraff and Taylor who attempt to show that it is a probable effect of the conditions existing beneath the earth's crust; by J. W. Gregory who believes that the distribution of continents might better be explained as due to vertical rather than horizontal movements; and by Singewald who takes a somewhat neutral attitude.

The discussion is concluded by Van der Grach in a summary of the views of the several contributors to the volume, with critical remarks on each.

The book is well worth reeading by all geologists and others who are interested in attempting to understand the reason for the distribution of land and sea on the globe. It is well written, well printed and sufficiently well illustrated to meet the demands of the discussion. The American Association of Petroleum geologists deserves much credit for bringing it out.

W. S. BAYLEY.

Beiträge zur Frage der Entstehung der Bolivianischen Kupfererzlagerstätten vom Typus Corocoro. By BRUNO GEIER. *Neues Jahrbuch für Mineralogie, etc.* B.B. 58, Abt. A, Pp. 1–42, 4 plates, 1927.

One of the recurrent subjects of discussion in the literature of economic geology is the origin of the native copper deposits of which the two outstanding examples are Lake Superior and Corocoro. This investigation is essentially a microscopic study of the collections from Corocoro and a group of less known and less important analogous occurrences in Bolivia and Chile contained in the museums of the Technical High School, Berlin, the Geological Survey in Freiburg i.Br., and the Mining School at Freiberg. The first two are the collections of Scheibe and Steinmann respectively.

Geier presents a more thorough petrographic description of the stratified rocks of Corocoro than is contained in the previous literature and emphasizes to even a fuller extent than did Singewald and Berry the participation of volcanic materials in them. The sandstones of the Vetas Series are better designated tuffites, and tuffaceous material occurs in the sandy beds of the Ramos Series. With the suggestion that the conglomerates represent true tuffs the reviewer is not in accord. The Pliocene age of the Corocoro sediments and igneous rocks as established since 1917 by the studies of Berry, Miller, and Singewald is accepted by Geier. It is surprising that despite the very definite evidence, paleontologic and petrographic, contained in their numerous writings on Corocoro that Lindgren still believes these rocks to be of Permian age (Mineral Deposits, 3d edition, 1928), the only basis this correlation has ever had being that red beds of Permian age are found in other parts of the world.

Because the mineralized Ramos are more numerous than the Vetas, Geier falls into the error of ascribing greater economic importance to the former. Most of the mines of the district are located on the Vetas.

The microstructure of the ore illustrated with microphotographs is described at some length. The native copper ore is considered to have been introduced mainly by impregnation and occurs as isolated grains in the matrix of the rock though in the richer ore the grains have coalesced and constitute the entire matrix. The copper sulphide ores show evidence of more intense metasomatism and are not confined to a replacement of the matrix alone. Pseudomorphs of chalcocite after native copper are described, and supergene chalcocite is recognized.

The deposition of native copper is ascribed to the influence of the host rock and the nature of the mineralizing solutions. The matrix of the cupriferous beds contains clay and kaolinic substance and easily decomposed volcanic glass. The bleaching of the red rock is due, not to a reduction of the ferric iron alone, but to an actual removal of the iron. The precipitation of metallic copper is referred to the absorptive action

of the kaolinic material. Persisting in the older ideas concerning the Lake Superior deposits, the author regards the absence of zeolites as sharply differentiating genetically the Corocoro ores from them. Because of the very limited solubility of copper sulphides even in alkaline polysulphides, he assumes the mineralizing solutions to have been acid thermal waters containing the metal in the form of chloride or bicarbonate and carrying small quantities of sulphuretted hydrogen and arseniurated hydrogen. The acids liberated by the absorption of the copper dissolved the iron oxide of the rock and bleached it. The dioritic magma of the region is accepted as the source of the solutions. The explanation is an ingenious one in line with the present tendency to the application of physical chemical principles in theories of ore deposition. The reviewer still believes, however, that less hypothetical and more probable is the assumption that the mineralizing solutions derived from this dioritic magma were not much different from other cupriferous magmatic emanations, and that the deposition of much native copper instead of all copper sulphide was determined by the environment in which ore deposition took place, that is, he still believes in the essential correctness of Steinmann's theory and the similarity in genesis of the Corocoro and Lake Superior deposits.

JOSEPH T. SINGEWALD, JR.

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The Geology of Venezuela and Trinidad. By R. A. LIDDLE. Pp. xxxix + 552, Plates 53, Figs. 22, Geol. Map. J. P. McGowan, Fort Worth, Texas, 1928. Price, $7.50.

In this comprehensive description of the geology of Venezuela and Trinidad is to be found the only systematic discussion of the geology of this area that is available. There have been descriptions of portions of the district, but nowhere except in the present volume is there a description of the district as a whole. The book is the result of five years study by the author. It contains not only an account of his own observations but also the contributions of many other workers, among them the geologists of the Pure Oil Company, to whose records the author was granted free access.

The book is in two parts, of which the first deals with the physiography, the stratigraphy, the structure and the economic geology of Venezuela, and the second with the same features of Trinidad. The physiography of each country is described in detail, but the greater portion of the volume is devoted to the description of their stratigraphy.

The discussion begins with a brief outline of the pre-Devonian history of the Venezuelan area with suggestions as to the correlation of the

Silurian and older schists. Then, beginning with the Devonian beds, the author describes in detail the rocks of the successive formations as observed in different portions of Venezuela, the greater portion of the space in the volume being, of course, occupied with the Mesozoic and Cenozoic formations. Many exposures are referred to and the reasons for placing them at one or the other horizon are given.

Following the outlining of the formations the author discusses as thoroughly as is possible, with the scant information at hand, the structure of the different portions of the country and follows this with an account of the economic products, mainly coal, iron, copper, sulphur, clay, bauxite, salt, gold, magnesite, asphalt, which is widely distributed, and petroleum. The producing oil fields are listed and described. Their daily production at the end of 1926 is given and the ranges in the specific gravity of the oil produced in each are stated.

The geology of Trinidad is discussed in the same manner as that of Venezuela. The oldest rocks are possibly pre-Silurian schists found in the North Range, which is an extension of the Coast Range of Venezuela. Above these are metamorphosed limestones which are believed to be Silurian. Over the remainder of the island are a few patches of Paleozoic and Mesozoic rocks; but the greater portion of its area is underlain by Cenozoic sediments. The only economic products of Trinidad are asphalt, manjak and petroleum.

The book ends with a bibliography of 5 pages and a very useful and comprehensive index of 40 pages.

The volume may be described as an excellent handbook of information relating to the geology of Venezuela and Trinidad. It is well printed and abundantly illustrated. It should be received with favor by all geologists interested in the search for oil in northern South America.

W. S. B.

Problems of Polar Research. By THIRTY-ONE AUTHORS. Amer. Geogr. Society Special Publication No. 7, New York, 1928. 479 pp., 42 maps, 25 diagrams, 30 figs., bibliography, index.

In this timely volume the scientific and not the adventurous side of polar exploration is considered. The authors are the foremost polar explorers and investigators, and include such well-known names as Nansen, Rasmussen, Stefansson, Mawson, Byrd, Wilkins, Ellsworth, and Nobile. The present knowledge is presented, and tasks for future investigation are pointed out. The discussions relate to geology, meteorology, botany, zoölogy, ethnology, glaciation. Exploration and navigation by airship and airplane are included. Both polar regions are discussed.

The book brings together a great mass of polar data valuable to the scientist and interesting to the serious reader. No one interested in polar

regions or polar exploration should be without it. It should be in every library. The book is a credit to the American Geographical Society, and Dr. Bowman is to be congratulated for having initiated and brought to fruition so valuable a symposium.

The Geography of the Polar Regions. By OTTO NORDENSKJÖLD and LUDWIG MECKING. Amer. Geogr. Society, Special Publication No. 8. New York, 1928. 359 pp., 107 figs., bibliography, index.

This is a companion volume to "Problems in Polar Research," and is two books under one title. Dr. Nordenskjöld's part, 90 pages, is a general characterization of polar geography, and treats of the climate, soils, land forms, life, ice and the ice age. It will interest every student of climatology and polar geography. Dr. Mecking's part is a detailed description of the physical features of the individual regions of the Arctic and Antarctic, and brings out the diversity of the polar regions. It comprises a mass of valuable detailed information. The book is one that every geographer and geologist will want to refer to.

ALAN BATEMAN.

The Determination of Minerals under the Microscope. By J. W. EVANS. Pp. xii + 110. Figs. 51. Thos. Murby & Co., London, England. Price $2.00.

This little book is a discussion of the theory of the action of crystals on polarized light. It follows the passage of the light along different paths through crystals and explains the effects produced, largely with the aid of diagrams. The methods of determining extinctions, pleochroism, the directions of fast and slow rays and the properties of optical figures are described in great detail and in a simple and extremely clear manner. Indeed the discussion of the optical axial figures is perhaps the most valuable part of the book. The volume should be of great help to the student beginning the study of optical crystallography and a good friend to the more advanced student, who wishes to brush up on methods which have become rusty through disuse.

W. S. B.

BOOKS RECEIVED

Oil and Gas Resources of the Ava-Campbell Hill Area. By T. B. Root. 27 pp., 4 figs., 3 pl. Rept. of Inves. No. 16, Illinois State Geol. Survey, Urbana, Ill., 1928. (Revised reprint, June.)

Mineral Industries of Ohio. By J. A. Bownocker and W. Stout. Geol. Surv. of Ohio, Bull. 33, 1928 (May).

A map and directory of producing firms.

Cements, Limes and Plasters. By E. C. Eckel. Third edit. 699 pp., 161 figs. John Wiley & Sons, New York, 1928 (May). Price, $7.00.

A well-known book thoroughly revised and brought up to date.

Geology and Origin of Silurian Salt of New York State. By H. L. Alling. New York State Mus. Bull. 275. 139 pp. Albany, 1928 (June).

Geological relations, chemistry; good review and discussion of origin.

The Story of Geology. By Allan L. Benson. 300 pp., illustrated. Cosmopolitan Book Corporation, New York, 1928 (May). Price, $5.00.

An interestingly written story in catchy and sometimes flippant language for the non-professional reader by a lay writer. No geologist could or would write it, but the material is sound though disconnected. The writer has read widely, digested well, and presents an entertaining discourse that interests the geologist and fascinates the lay reader. It is a needed book.

Principles of Valuation. By John A. Grimes and William Horace Craigue. 274 pp., tables, charts, index. Prentice-Hall, New York, 1928 (June). Price, $10.00.

Correlates all methods of valuation of mineral and other properties and shows how to value future fluctuating incomes. Contains valuable charts and tables. Every mineral company should have a copy.

Economic Geology of the Castlegate, Wellington, and Sunnyside Quadrangles, Carbon County, Utah. By Frank R. Clark. 165 pp., 22 pl., map, index. U. S. Geological Survey Bull. 793, 1928 (June).

Careful study of the geology and the character of the coals.

Water Resources of Virginia. By J. J. Dirzulaitis and G. S. Stevens. Pp. 510, pl. 8, Bull. 31, Virginia Geological Survey, Richmond, 1927 (June 1928).

Stream flow records of Virginia streams and summary of water power development on the Potomac River system.

SCIENTIFIC NOTES AND NEWS

H. G. Ferguson, of the U. S. Geological Survey, is engaged in making reconnaissance studies of the Hamilton district, Nevada, and mapping the Silver Peak quadrangle, also he will review some features of the Tonopah and Hawthorne quadrangles.

B. S. Butler left Tucson, Arizona, in June for a short visit to Santa Rita, New Mexico, and later went to the headquarters of the U. S. Geological Survey at Golden, Colo.

Adolph Knopf, of Yale University, is in California for the summer carrying on field work for the U. S. Geological Survey.

D. D. Irwin, formerly of Bisbee, Arizona, was a recent visitor in New Haven, Conn., on his way to England and Rhodesia.

D. H. McLaughlin, Professor of Mining at Harvard University, has been in Mexico on professional business.

H. D. Smith, of United Verde Copper Company, has returned from a month's trip to Jerome, Arizona.

G. R. Mansfield, of the U. S. Geological Survey, is doing investigation work in New Mexico and Texas on potash and nitrate, with headquarters at Boswell.

N. H. Darton, of the U. S. Geological Survey, is engaged in work relating to the revision of the geologic map of Texas.

Frederick G. Clapp has returned to Teheran after reconnaissance of geological and technological conditions in the oil fields of southern and western Persia and the new field in Iraq.

H. W. Hoots, who lately resigned from the U. S. Geological Survey, is engaged in petroleum work with the Union Oil Company of California.

E. T. Mellor, consulting geologist of the Rand Mines, Ltd., Johannesburg, has recently been visiting England.

Albert O. Hayes, of Rutgers University, has been appointed head of the department of geology there.

Frank C. Greene, formerly with the Skelly Oil Company, is now doing research work in stratigraphy for the Roxana Petroleum Corporation at Tulsa, Okla.

John A. Burgess, of San Francisco, Calif., is spending the summer in the Sudbury district of northern Ontario, making his headquarters in Toronto.

W. F. James, of the Canadian Geological Survey, has resigned his position to open an office at Amos, Quebec, as consulting mining geologist.

C. A. Heiland, professor of geophysics at the Colorado School of Mines, in Golden, presented a paper at Washington in May before the American Geophysical Union, on electric, radioactive and magnetic methods of geophysical prospecting. He has lately been visiting Mexico and California.

F. J. Alcock, of the Canadian Geological Survey, is examining the antimony deposits in the region of Lake George, New Brunswick.

Malcolm MacLaren recently visited the Lake George mine, New South Wales, which formerly produced copper, but has shown zinc, lead, silver and gold at depth.

Reginald F. Allen is now general manager of Jepson Metals, Ltd., a tin property near Cartagena, Spain.

N. W. Bass, of the U. S. Geological Survey, is continuing field work begun last year on the coal resources in Powder River County, Montana.

James L. Bruce, resident director of the Cyprus Mines Corporation, is in the United States with his family for a vacation, and will return to Cyprus in October or November.

A. J. Collier and C. E. Erdmann, of the U. S. Geological Survey, are engaged in field work on the geology and coal resources in McCone County, Montana.

R. T. Walker, of the U. S. Smelting Co., at Salt Lake City, Utah, recently made an examination of the Cerro Gordo Estelle properties near Keeler, Calif.

G. Townsend Harley has opened offices in Las Cruces, New Mexico, for consulting geological and mining practice.

J. F. Wright, of the Canadian Geological Survey, is to examine the Sherritt-Gordon mine and other properties in Manitoba, and map an area of several hundred square miles in that region.

Harley A. Sill is now consulting engineer and general manager for the San Nicolas Mining Company at Vincente Guerrero, Durango, Mexico.

C. S. Corbett will return in October from Batavia, Java, where he has served for the past three years as chief geologist of the Nederlansche Koloniale Petroleum Maatschappij (subsidiary of Standard Oil Company of New Jersey).

Waldemar Lindgren reports that subscriptions for the Annotated Bibliography have not yet reached the desired objective but that it now seems probable that the plan can be carried out.

A. C. Lawson has taken a trip to Canada to study the Precambrian further.

S. H. Cathcart who recently returned from South America is spending the summer in New Haven, Conn.

James Park of Otayo University, New Zealand, is visiting South Africa and England this summer.

G. H. Garrey of Philadelphia has gone to Denver from Arizona.

George Otis Smith has gone to Seattle and Montana in connection with his duties as President of the A. I. M. M. E.

I. M. Marshall is now superintendent of the Central Manitoba Mines, Manitoba, Canada.

T. L. Gledhill has resigned from the geological branch of the Ontario Bureau of Mines.

The Kansas Geological Society is to hold its second field conference August 26 to September 2. Parties are to start from Springfield, Missouri, and from Harrison, Arkansas. Further information can be obtained from L. W. Kesler, 1007 Union National Bank Building, Wichita, Kansas.

The Geological Survey of Canada has 52 field parties comprising about 250 persons in the field this season.

The 15th International Geologic Congress has just issued a supplement to the 2d circular regarding the meeting in South Africa in 1929, stating that rebates of 20 per cent. of fares will be given by certain steamship companies upon presentation of a Steamship Concession Certificate to Thomas Cook and Sons or to the steamship companies. Certificates will be sent to all who register. There is also given a complete list of steamship lines leaving each country and touching South Africa, with their service, routes, and length of passage. The Committee asks particularly that all applying for membership comply with the requests in the second circular. The Editor has a few extra copies of the supplement for those who desire them.

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